A Practical Approach to Solve Power System Constraints With Application to the Spanish Electricity Market

Enrique Lobato Miguélez, Luis Rouco Rodríguez, Member, IEEE, Tomás Gómez San Román, Member, IEEE, Francisco M. Echavarren Cerezo, Ma Isabel Navarrete Fernández, Rosa Casanova Lafarga, and Gerardo López Camino

Abstract—The solution of power system constraints is an important issue that has to be addressed to achieve a fair operation of a competitive electricity market. In the Spanish electricity market, the System Operator (SO) is in charge of determining the technical feasibility of the generation dispatch provided by the Market Operator (MO). An optimal solution method of power system constraints in the Spanish market must take into account the connection of off-line units to solve both branch overloads and voltage constraints, the adjustment of voltage control resources, the solution of the postulated n-1 and n-2 contingencies with a preventive criteria and the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units. This paper details the management of power system constraints in the Spanish market, and contains a comprehensive review of solution methods of power system constraints. In addition, the paper proposes a novel approach to solve Spanish power system constraints that overcomes the limitations of existing methods, by decoupling the solution of branch overloads and voltage constraints.

Index Terms—Congestion management, optimal power flow, power system dispatch, security assessment, unit commitment.

I. INTRODUCTION

THE solution of power system constraints is an important issue that has to be adequately addressed for a fair operation of a competitive electricity market. The Spanish electricity market, as it started on January 1, 1998, is based on two separate entities [1]: the MO and the SO. The MO receives the bidding of generation and demand for each hour of the following day, and clears the market according to economic criteria. The SO is in charge of detecting and eliminating the power system constraints after the market has been cleared.

Branch overloads and voltage constraints are solved in Spain by increasing and decreasing the generation of connected units, and connecting off-line ones. The start up cost of the new generators to be connected, internalized in the fixed income term of the generator offer, plays a key role in the solution of voltage constraints in the Spanish electricity market. The coupled solution of voltage constraints for the 24 hourly scenarios differs from the individual solution for each hourly scenario. Hence, the start up cost couples the daily solution along the 24 hourly periods.

As it will be justified in the following section that reviews the Spanish regulation concerning the solution of power system constraints in the Spanish market, an optimal solution method must take into account the connection of off-line units to solve both branch overloads and voltage constraints, the inclusion of voltage resources as control variables in the optimization, the solution of the postulated contingencies with a preventive criteria and the consideration of the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units. The network must be represented with the complete ac power flow network model in order to solve voltage constraints. The problem under consideration consists of a big size non-linear optimization problem that contains integer variables corresponding to the start up decisions of off-line units and the state of the shunt reactors and capacitors.

No algorithm exists in the literature that meets all the required features for application to a real size system such as the Spanish power system. This paper reviews the existing methods that have been proposed in the literature to solve power system constraints. In addition, it describes the novel approach of the authors to solve Spanish power system constraints, overcoming the limitations of existing methods complying with the required features.

The proposed method builds the 24 hourly scenarios for the day ahead and addresses separately branch overloads and voltage constraints in each scenario.

Each hourly scenario is built determining the network topology, the active and reactive power loads of each bus and the generation of each generator. The network topology is determined from the maintenance scheduling of the elements of the transmission system. The active and reactive power loads of each bus are computed from the total demand and the active and reactive power factors of each bus. The Spanish system operator obtains the generation of each unit from the market clearing and the wind power prediction provided by a tool called SIPREOLICO [42]. Initial values of generator voltages, transformer ratios and shunt reactors and capacitors required to solve the load flow problem are obtained from real time scenarios of the power system provided by the state estimator of the energy management system.

After solving branch overloads in each hourly scenario, the optimal solution of voltage constraints is found in two steps.
Firstly, the decoupled solution of each hourly scenario is computed modeling the network by an ac power flow model. Finally, the coupled solution of voltage constraints in the 24 hourly scenarios is calculated taking as input the individual decoupled solution of each hourly scenario and the bus voltage sensitivities with respect to active and reactive injection of nonconnected units. In addition, after solving power system constraints, an optimal power flow is carried out with each hourly scenario to minimize transmission losses and maximize generator reactive margins.

The aim of this paper is to provide an overview of the complexity of the problem and justify the appropriateness of the strategy of dividing the complex problem under consideration in easier problems, maintaining enough accuracy in the solution. The authors have presented in other papers the detailed mathematical formulation of the different stages comprising the method [29], [35], [39], [40]. The proposed optimization approach described in this paper has been included in a tool to analyze and solve power system constraints in the Spanish electricity market, which has been developed for Red Eléctrica de España, the Spanish SO.

The paper has been organized as follows. Section II reviews the Spanish regulation that rules the solution of power system constraints. Section III contains a comprehensive review of existing solution methods of power systems constraints. The proposed approach to solve power system constraints in the Spanish electricity market is detailed in Section IV. The analysis and solution of branch overloads is addressed in Section V; Section VI is dedicated to the analysis and solution of voltage constraints. Section VII illustrates the performance of the algorithm with an actual example of the operation of the Spanish power system. Finally, conclusions are given in Section VIII.

II. REVIEW OF THE SPANISH REGULATION

This section reviews the Spanish regulation concerning the solution of power system constraints. It includes a general overview of the technical constraints solution process, the revision of the security criteria that applies to the operation of the Spanish power system, a convenient classification of Spanish power system constraints and also the description of the remuneration of units that modify their output.

A. General Overview of the Solution Process

The SO is in charge of detecting and eliminating the power system constraints after the market has been cleared. The power system constraints are solved by increasing and decreasing the generation of connected units, and connecting off-line ones. The generation redispatch is computed by the MO minimizing the total system cost, and is sent afterwards to the MO. In addition, the SO establishes the list of fixed-dispatch units in which the decrease of generation worsens the voltage profile. The MO adds the generation redispatch provided by the SO to the market clearing and restores the generation-demand balance considering that fixed-dispatch units can not reduce their output. Both generation redispatch and adjustment of the generation-demand balance is computed according to the generation offers submitted by the market participants into the market.

A generator offer consists of a set of energy-price blocks for each hour of the following day. A minimum income complex condition is also submitted in the offer. This condition consists of a fixed income term and a variable income term. The fixed term internalizes the start up cost of the generating unit and the variable income term represents the medium energy cost.

It should be noted that the described process is valid only for the daily market. However, in order to avoid new transmission constraints, the output of the solution process is taken into account to limit the transactions that the market participants are allowed to make in the following markets (secondary reserve market and intraday markets). No real-time markets have been developed in Spain. Unexpected transmission constraints are managed with the deviation management market and the tertiary reserve market, and as a last resort, by means of emergency measures ordered by the system operator [41].

B. Security Criteria of the Spanish Power System

The security criteria of the Spanish power system require that power system variables (branch power flows and bus voltages) must be within their limits not only in normal operating condition but also when any credible contingency occurs [2]. The contingencies under consideration are the loss of any generator, transmission line or transformer, the loss of the double circuits that share more than 30 km and the combined loss of key generator and transmission lines. It should be noted that the branch power flow and bus voltage limits in case of n-1 and n-2 contingencies are different from the limits under normal operating condition. Spanish regulation imposes a preventive operation of the power system, i.e., for every contingency postulated, all system variables are within limits without making any corrective action.

C. Classification of Power System Constraints

Power system constraints are classified in the Spanish system in 1) branch overloads and 2) bus voltage violations.

Branch overloads are solved by increasing and decreasing power in connected units and in some cases, connecting off-line ones. Practical overloads in Spain do not require the disconnection of on-line units. This type of constraints is not frequent within the Spanish system.

Voltage constraints are solved by connecting a set of off-line generators, and reducing an equal amount of power in the most expensive connected ones. Since in Spain voltage constraints are always due to low voltages, the connection of off-line generators is essential to remove the violations: they provide reactive support in the importing areas and also inject active power in the system, which reduces the power transfers between exporting and importing areas (the effect of injecting active power to increase the voltage profile is significant when a power system is close to the critical loading condition of the nose curve [3]–[5]). In addition, shutting down on-line units is not considered in the solution in order to keep the reactive support that they provide to the system.

Voltage constraints are common within the Spanish system and can only be solved by generators located in the areas where they occur. A dc power flow network model does not take into account the voltage profile. Thus, an ac representation of
the network is needed. It should be noted that the operation of the power system with an adequate voltage profile reduces the number of off-line units to be connected to solve voltage constraints and therefore the total system cost of the generation dispatch. Thus, voltage resources must be included as control variables of an optimal solution method.

D. Remuneration of Units That Modify Their Output

The units that increase their output are paid at their offer price. Generators that decrease their output are not compensated for their income reduction. Therefore, the total system cost is computed by adding the offer cost of new connected generation, and subtracting the decreased energy times the system marginal price. The SO must solve power system constraints obtaining the generation redispach that minimizes the total system cost.

A special case of units that increase their output are new connected ones that have not been cleared in the market. When a unit is connected, the energy cost and the total income cost are computed. The energy cost represents the remuneration corresponding to the set of energy-price blocks of the generator offer

\[ \text{Energy cost} = \sum_{\text{blocks}} \sum_{\text{hours}} \text{block price} \cdot \text{block energy}. \] (1)

The total income cost represents the remuneration corresponding to the minimum income complex condition of the generator offer, and is computed as follows:

\[ \text{Income cost} = \text{number startups} \cdot \text{startup cost} + \text{energy price} \cdot \text{total daily energy}. \] (2)

The income that the connected generator receives (which is its contribution to the total system cost of solving power system constraints) is the maximum of these two quantities

\[ \text{Income} = \max(\text{Energy cost}, \text{Income cost}) \] (3)

It should be noted that, within the process of solving power system constraints, the System Operator does not need fulfill generator ramp limits. Spanish regulation establishes that the market participants are responsible for eliminating generator ramp violations within intradaily markets [1].

III. REVIEW OF EXISTING METHODS TO SOLVE POWER SYSTEM CONSTRAINTS

An optimal solution method of power system constraints in the Spanish market must consider the connection of off-line units to solve both branch overloads and voltage constraints, the adjustment of voltage control resources, the solution of the postulated n-1 and n-2 contingencies with a preventive criteria and the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units.

Fig. 1 depicts the required features of the searched optimal solution method of power system constraints in the Spanish electricity market. No algorithm has been developed in the literature that meets all the required features. In the literature there exist two types of algorithms that meet some of the desired requirements of the problem under consideration: 1) security constrained unit commitment algorithms and 2) security constrained optimal power flow algorithms.

A. Security Constrained Unit Commitment Algorithms

Unit commitment algorithms (UCA) optimize a power system within a defined time scope, given a set of input conditions. In the short term (from one week up to four weeks), UCA determine the start up and shut down decisions of thermal units, and the optimal power output of hydro, pumping and thermal units in the specified time scope. Thus, UCA consider the connection of off-line units and the time coupling between each period.

Security constrained unit commitment algorithms (SCUCA) include network constraints within the UCA. Most of them model the network with a dc power flow [6]–[12]. The dc power flow network model allows the solution of branch overloads, but cannot address voltage constraints. Sometimes, SCUCA with a dc power flow network model are used internalizing branch power flow and bus voltage limits (in normal operating condition and under the occurrence of contingencies) by means of ATC values [13], as happens in the optimization model to solve power system constraints in the Californian power market [14], [15]. However, the internalization of voltage constraints within ATC values is not precise and requires a high computational burden [16]–[18]. Some SCUCA described in the literature attempt to model voltage constraints with the ac power network model, but either they are applied to small case systems and/or do not model contingency constraints [6], [19]–[21].

In conclusion, the SCUCA developed in the literature do not satisfy all the practical requirements depicted in Fig. 1 of an optimal solution method of power system constraints for the Spanish market. Fig. 2 illustrates the features that existing security constrained unit commitment algorithms meet for application to the solution of power system constraints of a real size system.

B. Security Constrained Optimal Power Flow Algorithms

Optimal power flow algorithms (OPF) optimize the operation of a scenario that represents the state of a power system for a given instant of time. The optimization is carried out with individual scenarios and thus, time relationship between different scenarios is not considered in an OPF. From the definition it follows that OPF algorithms always model the network. Different objective functions can be specified in an OPF depending on
the designed application. In addition, the detail of the network model (ac or dc) included in the OPF varies between different applications [22]–[24].

Security constrained optimal power flow algorithms (SCOPF) are designed to obtain a secure state of the power system by adjusting the available control resources of the power system, incorporating the preventive or corrective operation criteria for the postulated contingencies [25].

Concerning the solution of power system constraints in the Spanish power system, the main limitations of the existing SCOPF algorithms developed in the literature are as follows.

- Most SCOPF do not take into account the effect of the injection of active power to increase the voltage profile, assuming a decoupled active/reactive formulation [26]–[28].
- Most SCOPF that include contingency constraints regard n-1 contingencies but not n-2 contingencies.
- None of the existing SCOPF algorithms consider the connection of off-line units with binary variables, to solve branch overloads and voltage constraints.
- Most of the SCOPF references present results for small size test systems.

Fig. 3 outlines the features that existing security constrained optimal power flow algorithms meet for application to the solution of power system constraints of a real size system.

IV. PROPOSED APPROACH FOR SOLVING POWER SYSTEM CONSTRAINTS APPLIED TO THE SPANISH MARKET

This section contains the proposed approach for obtaining the optimal solution of power system constraints in the Spanish electricity market, complying with the requirements depicted in Fig. 1. In addition, the proposed method contains an OPF carried out after solving power system constraints with each hourly scenario, in order to minimize transmission losses and maximize generator reactive margins [29]. It should be noted that an interval of an hour is appropriate to optimize the operation of a power system by means of transmission losses minimization [30].

The overall process is depicted in Fig. 4. It comprises two stages: feasibility and optimality. The feasibility stage obtains the generation redispatch and adjustment of the voltage control resources (generator voltages, transformer taps and state of shunt reactors and capacitors), minimizing the total system cost and complying with the Spanish security criteria. Once feasibility is obtained, the voltage control resources are fine tuned in the optimality stage for each hourly scenario, running the OPF described in [29].

The strategy of dividing an OPF problem into a feasibility stage and an optimality stage has also been proposed in [31]: firstly voltage violations are solved by a heuristic algorithm [32] (feasibility stage), and afterwards transmission losses are minimized using the subgradient method [33] (optimality stage).

Within the feasibility stage, branch overloads and voltage constraints are addressed separately.

At first, branch power flow limit violations are solved, in normal operating condition and in the postulated contingencies with preventive criteria. Branch overloads are addressed using a dc linear network model that approximates branch reactive power flows. Some contingencies require the connection of off-line units to remove overloads. These new connected units change the reactive and active system profile and may modify the number and the severity of the contingencies that result in bus voltage violations, justifying the prior solution of branch overloads before addressing voltage constraints. Since in the Spanish case, the branch overloads that require the connection

Authorized licensed use limited to: UNIVERSIDAD PONTIFICIA DE COMILLAS. Downloaded on June 18,2021 at 11:17:10 UTC from IEEE Xplore. Restrictions apply.
of an off-line unit can only be removed by the start up of this specific generator, in practice the solution of branch overloads is not coupled along the 24 hourly scenarios.

Once branch overloads have been eliminated, bus voltages violations that arise under the occurrence of contingencies are solved with a preventive criteria. The proposed method divides the problem in two steps: (a) decoupled solution of voltage constraints, and (b) coupled solution of voltage constraints.

Initially, the decoupled solution of each hourly scenario is obtained representing the network by the complete ac power flow model. Within each hour, the fixed term of the minimum income condition of the generator offer models the start up cost of an off-line unit.

The second step computes the coupled solution of voltage constraints in the 24 hourly scenarios taking as input the individual decoupled solution of each hourly scenario (active and reactive power injection of the new connected units) and the bus voltage sensitivities of violated buses with respect to active and reactive injection of nonconnected units. Although in theory the generation redispacht that solves voltage constraints could induce new branch overloads, in practice it does not occur because the solution of low voltages requires the injection of active and reactive power in the importing areas where there is a deficit of power. Thus, no further iteration within the feasibility stage is required.

The main advantages of the proposed approach for solving power system constraints in the Spanish electricity market are:
- The decomposition of the complete problem into different subproblems minimizes the risk of failure of the algorithm in finding the optimal solution of the feasibility stage (although it cannot be guaranteed that the solution is the global optimum of the problem, it is a local optimum satisfactory enough in practice). This is an essential requirement, because the electricity market cannot be operated if the solution to power system constraints cannot be given.
- The method proposed allows identifying which generator redispatch corresponds to which violation, increasing the transparency in the market operation.

The next two sections detail the process of solving branch overloads and voltage constraints within the feasibility stage. The mathematical formulation of the optimality stage is contained in [29].

V. ANALYSIS AND SOLUTION OF BRANCH OVERLOADS

For each hourly scenario, the analysis and solution of branch overloads in the Spanish System is performed in three steps: 1) contingency analysis, 2) preventive active power dispatch, and 3) classification of results.

A. Contingency Analysis

This step detects the postulated contingencies that result in nonadmissible branch overloads. First, a dc contingency analysis routine is used as a screening tool to identify which contingencies may cause overloaded branches. Branch reactive power flows are approximately taken into account within the dc contingency analysis by reducing the branch rating according to the prefault power factor. The contingencies selected by the dc contingency analysis are fully analyzed by an ac contingency module to confirm the overloads and to provide post fault power factors of the overloaded branches so that the preventive active power dispatch can take into consideration the branch reactive power flows [34].

B. Preventive Active Power Dispatch

This step solves branch overloads in normal operating condition and under the occurrence of the contingencies detected in the contingency analysis (incorporating a preventive criteria). The preventive active power dispatch has been formulated as a mixed-integer linear optimization program (the connection of off-line units is modeled with binary variables) that computes the minimum cost variation of the generation dispatch so that the overloaded branches are alleviated. The objective function consists of minimizing the cost of the deviation of the generation dispatch. The equality constraints are the network equations according to the dc load flow model and the generation-demand balance constraint. The inequality constraints are the branch power flows in normal operating conditions and in case of contingencies, where the reactive branch power flows are taken into account by reducing branch ratings in proportion to the post fault power factor (it is assumed that branch reactive power flows do not vary significantly when the active generation profile is modified [34]). The detailed mathematical formulation of the preventive active power dispatch, and its performance illustrated with an actual example of the Spanish power system, can be found in [35].

C. Classification of Results

The preventive active power dispatch obtains the generation redispacht that solves branch overloads and at the same time obtains a generation-demand balance. However, Spanish regulation establishes that the SO must send to the MO only the generator redispacht that remove the overloads. The adjustment of the generation-demand balance is computed by the MO. Hence, the units that vary their output in the preventive active power dispatch must be separated and classified in:
- Efficient units that remove the overloads. They are located in the system close to the overloads.
- Compensation units that restore the generation-demand balance at the minimum system cost. Their location does not depend on the location of the system overloads.

The classification is performed computing the following indices for each generator:

- $A_g$ total active power alleviated by each generator redispacht, in branches overloaded in normal operating condition and due to contingencies.

Post-fault branch power flows are calculated using linear sensitivities with respect to the active injection [35], [36]. It should be noted that the value of the linear sensitivities used to compute $A_g$ depends on the location of the slack bus of the system that compensates the injected power at each bus. However, if the slack bus of the system is selected in a well-meshed area where overloads rarely occur, the influence of the slack bus location is diminished. In other words, a convenient slack bus corresponds to a generator far from the frequent overloads,
in which the variation of slack active power has no effect. In the Spanish power system, the slack bus corresponds to the ALDEADAVILA 1000 MW hydro generator located in the northwest area of the Spanish power system. The electric area of this generator is well meshed and in practice, this slack bus selection does not influence the classification results.

- $E_g^i$: efficiency achieved by each generator redispatch. It corresponds to the active power alleviated by redispatching 1 MW in the unit:

$$E_g^i = \frac{A_g}{\Delta \text{unit output}}$$

- ER$_g^i$(%): relative efficiency achieved by each generation redispatch: corresponds to the normalization of the efficiency of each unit with respect to the efficiency of the most effective unit:

$$\text{ER}_g^i(\%) = 100 \cdot \frac{E_g^i}{\max E_g^i}$$

Effective units correspond to those whose relative efficiency ER$_g^i$(%) is greater than a selected threshold and the rest of units are classified as compensation units.

VI. ANALYSIS AND SOLUTION OF VOLTAGE CONSTRAINTS

The analysis and solution of voltage constraints comprises the following steps: 1) contingency analysis, 2) decoupled preventive solution of each hourly scenario, and 3) coupled preventive solution of the 24 hourly scenarios.

A. Contingency Analysis

An ac contingency analysis using a fast decoupled load flow algorithm is carried out, in order to find the postulated contingencies that result in voltage constraints. The 1P-1Q iteration method [37] has been implemented as a screening tool to detect bus voltage limit violations. Contingencies that result in voltage problems using the 1P-1Q iteration method are fully solved within the specified tolerance. The contingencies that result in lack of convergence of the fast decoupled load flow algorithm are subsequently analyzed using a nondivergent fast decoupled load flow algorithm [38].

B. Decoupled Preventive Solution of Each Hourly Scenario

The preventive decoupled solution addresses the bus voltage limit violations (reactive generation limit violations are also taken into account when the load flow does not converge imposing generator reactive limits) due to contingencies, by connecting a set of off line generators and adjusting the voltage control resources (generator voltages, transformer taps and the status of shunt reactors and capacitors). Balance demand is achieved reducing generation in the most expensive units (i.e., the last units cleared in the market) considering that fixed-dispatch units cannot decrease their output. The network is represented by the complete ac power flow model.

The new connected generators provide reactive support in the importing areas and also inject active power in the system, which reduces the power transfers between exporting and importing areas.

Two different algorithms have been developed to obtain the optimal decoupled solution of voltage constraints in the Spanish electricity market.

Algorithm 1 consists of an iterative process that connects one generator in each iteration to solve the voltage and reactive violations that arise under the occurrence of the postulated contingencies. The generator to be connected in each iteration is selected by a mixed-integer linear optimization program that minimizes the total system cost of redispatching generation. Algorithm 1 does not consider voltage control resources as control variables. Hence, it is assumed that the voltage profile has been adjusted previously. The objective function is formulated in each iteration as the minimization of the total system cost (cost of connecting new units and increasing generation in connected ones and subtracting the saved cost of the generators that reduce their output) and the cost of leaving voltage violations in the system.

Algorithm 2 has also been formulated as an iterative process. In each iteration, voltage control resources are adjusted and off-line generators are connected to solve the voltage and reactive violations that arise under the occurrence of the postulated contingencies. The objective function of algorithm 2 is similar to algorithm 1, including additional cost terms of the adjustment of voltage control resources.

The detailed mathematical formulation of both algorithms is included in [39]: their performance is illustrated considering the solution of voltage constraints of an actual hourly scenario of the Spanish electricity market. In addition, the reference contains a thorough comparison between them from an economic and technical point of view.

C. Coupled Preventive Solution of the 24 Hourly Scenarios

This step obtains the coupled solution of voltage constraints in the 24 hourly scenarios of the Spanish electricity market. The input data of the problem consists of the individual decoupled solutions for each hourly scenario and the bus voltage sensitivities with respect to active and reactive injection of nonconnected units.

The coupled preventive solution module consists of an optimization program that minimizes the total system cost of the new connected generators. Its mathematical formulation and its application to an actual example of the operation of the Spanish system can be found in [40].

VII. CASE STUDY

The performance of the proposed algorithm is illustrated using an actual example of the operation of the Spanish power system corresponding to February 2001. The Spanish power system model includes representation of the French, Portuguese and Moroccan systems. The whole model contains 1208 buses, 1852 branches and 479 generators. The contingencies to be analyzed and solved correspond to 928 branch contingencies, 64 generator contingencies, 33 double circuit contingencies and 77 combined contingencies of a generator and a transmission line. The voltage control resources that are available in the system are 280 generator bus voltages, 100 transformer taps variables and 48 shunt reactors/capacitors. The size of the sub problems
of the algorithm is about 7000 variables (90 corresponding to binary variables), 10,000 constraints and 35,000 nonzero elements.

Peak hour 11 has been solved in a decoupled manner. Table I contains the generation redispatch to remove branch overloads in normal operating condition and in case of contingencies. For each generation redispatch, the classification indices defined in Section V have been computed. Selecting a minimum relative efficiency threshold of 30%, the first three actions of Table I are classified as effective, while the rest correspond to compensation results. It should be noted that in practice, the designed classification method is robust: for the example presented the same classification is obtained selecting a relative efficiency threshold between 4% and 93%. It should be noted that the effective units ESCOMBRE1, ESCOMBRE2, ESCOMBRE3 were not cleared in the market. This fact demonstrates that in some cases the connection of off-line units is required to solve overloads and thus, they need to be included as decision variables in the preventive active power dispatch.

Fig. 5 illustrates the number of voltage control resources adjusted in the solution of voltage constraints for peak hour 11, for each electric area of the Spanish power system. It should be noted that the main adjustments are located in the importing areas east, central, and south.

Figs. 6 and 7 compare the decoupled and coupled solution of voltage constraints. Each table contains the power in MW connected in each generator. The reduction of the number of start-up decisions of thermal units in the coupled solution (the decoupled solution contains 4 start-up decisions of thermal generators FOIX, S. ADRIAN, CASTELL2, and ALGECIR2) generator achieves a 52% system cost reduction with respect to the decoupled solution of each hourly scenario.

For the case example presented, branch overloads were solved in 21 seconds (in a RS6000-44P-270 machine with 375 MHz and 1024 MB of RAM memory), the decouple solution of hour 1 took 62 seconds and the coupled solution for the whole day was obtained in 4 seconds. It should be noted that the total time very much depends on the number of contingencies that result in overloaded branches and voltage violations.

In daily operation, the slowest case experienced by the authors took less than 30 minutes to solve transmission constraints for the 24 hours of the daily market (it should be pointed that the system operator has an upper limit of two hours to complete the analysis and solution process).

VIII. CONCLUSION

An optimal solution method of power system constraints in the Spanish market must take into account the connection of off-line units to solve both branch overloads and voltage constraints, the inclusion of voltage resources as control variables in the optimization, the solution of the postulated contingencies with a preventive criteria and the consideration of the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units. The network must be represented with the complete ac power flow network model in order to solve voltage constraints.

A comprehensive literature survey of existing methods for solving power system constraints has been provided, and their limitations concerning their application to the Spanish case have been outlined. The revision includes security constrained unit commitment algorithms and security constrained optimal power flow algorithms.

This paper has proposed a practical approach to obtain an optimal solution of power system constraints in the Spanish power system. The method decouples the solution of branch overloads coupled solution contains 3 start up decisions of thermal units CASTELL2, CERCs, and ALGECIR2) generator achieves a 52% system cost reduction with respect to the decoupled solution of each hourly scenario.

For the case example presented, branch overloads were solved in 21 seconds (in a RS6000-44P-270 machine with 375 MHz and 1024 MB of RAM memory), the decouple solution of hour 1 took 62 seconds and the coupled solution for the whole day was obtained in 4 seconds. It should be noted that the total time very much depends on the number of contingencies that result in overloaded branches and voltage violations.

In daily operation, the slowest case experienced by the authors took less than 30 minutes to solve transmission constraints for the 24 hours of the daily market (it should be pointed that the system operator has an upper limit of two hours to complete the analysis and solution process).

VIII. CONCLUSION

An optimal solution method of power system constraints in the Spanish market must take into account the connection of off-line units to solve both branch overloads and voltage constraints, the inclusion of voltage resources as control variables in the optimization, the solution of the postulated contingencies with a preventive criteria and the consideration of the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units. The network must be represented with the complete ac power flow network model in order to solve voltage constraints.

A comprehensive literature survey of existing methods for solving power system constraints has been provided, and their limitations concerning their application to the Spanish case have been outlined. The revision includes security constrained unit commitment algorithms and security constrained optimal power flow algorithms.

This paper has proposed a practical approach to obtain an optimal solution of power system constraints in the Spanish power system. The method decouples the solution of branch overloads coupled solution contains 3 start up decisions of thermal units CASTELL2, CERCs, and ALGECIR2) generator achieves a 52% system cost reduction with respect to the decoupled solution of each hourly scenario.

For the case example presented, branch overloads were solved in 21 seconds (in a RS6000-44P-270 machine with 375 MHz and 1024 MB of RAM memory), the decouple solution of hour 1 took 62 seconds and the coupled solution for the whole day was obtained in 4 seconds. It should be noted that the total time very much depends on the number of contingencies that result in overloaded branches and voltage violations.

In daily operation, the slowest case experienced by the authors took less than 30 minutes to solve transmission constraints for the 24 hours of the daily market (it should be pointed that the system operator has an upper limit of two hours to complete the analysis and solution process).

VIII. CONCLUSION

An optimal solution method of power system constraints in the Spanish market must take into account the connection of off-line units to solve both branch overloads and voltage constraints, the inclusion of voltage resources as control variables in the optimization, the solution of the postulated contingencies with a preventive criteria and the consideration of the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units. The network must be represented with the complete ac power flow network model in order to solve voltage constraints.

A comprehensive literature survey of existing methods for solving power system constraints has been provided, and their limitations concerning their application to the Spanish case have been outlined. The revision includes security constrained unit commitment algorithms and security constrained optimal power flow algorithms.

This paper has proposed a practical approach to obtain an optimal solution of power system constraints in the Spanish power system. The method decouples the solution of branch overloads coupled solution contains 3 start up decisions of thermal units CASTELL2, CERCs, and ALGECIR2) generator achieves a 52% system cost reduction with respect to the decoupled solution of each hourly scenario.

For the case example presented, branch overloads were solved in 21 seconds (in a RS6000-44P-270 machine with 375 MHz and 1024 MB of RAM memory), the decouple solution of hour 1 took 62 seconds and the coupled solution for the whole day was obtained in 4 seconds. It should be noted that the total time very much depends on the number of contingencies that result in overloaded branches and voltage violations.

In daily operation, the slowest case experienced by the authors took less than 30 minutes to solve transmission constraints for the 24 hours of the daily market (it should be pointed that the system operator has an upper limit of two hours to complete the analysis and solution process).

VIII. CONCLUSION

An optimal solution method of power system constraints in the Spanish market must take into account the connection of off-line units to solve both branch overloads and voltage constraints, the inclusion of voltage resources as control variables in the optimization, the solution of the postulated contingencies with a preventive criteria and the consideration of the coupling of the solution in the 24 hourly scenarios due to the start-up cost of nonconnected units. The network must be represented with the complete ac power flow network model in order to solve voltage constraints.

A comprehensive literature survey of existing methods for solving power system constraints has been provided, and their limitations concerning their application to the Spanish case have been outlined. The revision includes security constrained unit commitment algorithms and security constrained optimal power flow algorithms.

This paper has proposed a practical approach to obtain an optimal solution of power system constraints in the Spanish power system. The method decouples the solution of branch overloads
and voltage constraints, minimizing the risk of failure in finding the optimal solution method and allowing the identification of the generation redispatch that correspond to each violation and thus, increasing the market transparency.

ACKNOWLEDGMENT

This work has been developed under the research project ARO developed by software enterprise Indra and Comillas University for Red Eléctrica de España, the Spanish System Operator. The authors gratefully acknowledge the contributions of F. Blanco, F. Cacho, and M. Pezic of Red Electrica. Thanks also to T. Doménguez, P. Saucedo, N. Hernández, M. Pezic, J. Moreno, E. Acosta, R. de Dios, J. L. Fernandez, M. Llorens (Red Electrica), J. García-Castillejo (now with Endesa) and A. Cortés (now with Gas Natural) for their fruitful comments.

REFERENCES

Enrique Lobato Miguélez was born in Burgos, Spain, in 1974. He received the degree of Electrical Engineer in 1998 and the Ph.D. degree in 2002, from Universidad Pontificia Comillas, Madrid, Spain.

Since June 1998, he has been a Researcher at the Instituto de Investigación Tecnológica, Universidad Pontificia Comillas. His areas of interest include analysis, planning, operation and economics in electric power systems. He has participated in several research projects for different firms related with the energy industry.

Francisco M. Echavarren Cerezo was born in Madrid, Spain, in 1977. He received the degree of Electrical Engineer from Universidad Pontificia Comillas in 2001.

Since June 2001, he has been a Research Assistant at the Instituto de Investigación Tecnológica, Universidad Pontificia Comillas. His areas of interest include modeling, analysis, and simulation of power systems.

Luis Rouco Rodríguez (S’89–M’91) obtained the Electrical Engineer degree and the Ph.D. degree from Universidad Politécnica de Madrid, Spain, in 1985 and 1990.

He is Associate Professor with the School of Engineering of Universidad Pontificia Comillas. His areas of interest are modeling, analysis, simulation, and identification of electric power systems. He has been a Visiting Researcher at Ontario Hydro, MIT, and ABB Power Systems.

Ma Isabel Navarrete Fernández was born in Albacete, Spain, in 1960. She received the degree in physics from the Universidad Complutense de Madrid, Spain, in 1982.

Since 1983 she has been working for Indra SSI as a Software Engineer. She belongs to the Business Intelligent Department. She has supervised the development of a number of projects for the energy sector.

Tomás Gómez San Román received the Doctor Ingeniero Industrial degree from the Universidad Politécnica, Madrid, Spain, in 1989, and the degree of Ingeniero Industrial in electrical engineering from the Universidad Pontificia Comillas (UPCO), Madrid, in 1982.

He joined Instituto de Investigación Tecnológica (IIT-UPCo) in 1984 where he has been Director from 1994 to 2000. From 2000 to 2002, he was the Vice Chancellor of Research, Development and Innovation at UPCO. He has significant experience in industry joint research projects in the field of electric energy systems in collaboration with Spanish, Latin-American, and European utilities. His areas of interest are operation and planning of transmission and distribution electrical systems, power quality assessment and regulation, and economic and regulatory issues in the electrical power sector.

Rosa Casanova Lafarga was born in Madrid, Spain, in 1964. She received the master in artificial intelligence from the Universidad Politécnica de Madrid in 1988.

Since 1988 she has been working for Indra SSI as an analyst programmer in the Business Intelligent Department. She has participated in the development of a number of projects for the energy sector.

Gerardo López Camino received the Electrical Technical Engineer degree in 1975.

Since 1983, he has been working for Red Eléctrica de España. He has been Shift-Chief at the Electrical Operation Center of the Spanish System for 12 years. His main responsibilities include the Operator Training Simulator of Red Eléctrica and the development of tools for analysis of power system constraints.