Sizing and Siting STATCOM Devices in the Portuguese Transmission System for Improving System Security

P.N. Pereira Barbeiro[*1], C.L. Moreira[*2], H. Keko[*3], H. Teixeira[*4],Nuno Rosado [†5], João Moreira[†6], Reis Rodrigues[†7]

[1]pedro.p.barbeiro@inescporto.pt, [2]carlos.moreira@inescporto.pt, [3]hkeko@inescporto.pt, [4]hst@inescporto.pt, [5]nuno.rosado@ren.pt, [6]joao.moreira@ren.pt,[7] reisrodrigues@ren.pt

[*]INESC TEC - INESC Technology and Science (formerly INESC Porto), Rua Dr. Roberto Frias, 378, Porto 4200-465, Portugal
[†]REN, Redes Energéticas Nacionais, S.A., Av. dos Estados Unidos da América, 55, Lisboa 1749-061, Portugal

Abstract - This paper presents a methodology for siting and sizing STATCOM devices in the Portuguese transmission system in order to improve system security following severe grid faults. Security issues arise since the Portuguese transmission system incorporates significant levels of wind generation without fault ride through and reactive current injection capabilities during grid faults. Being the Transmission System Operator (TSO) responsible for assuring system security, the goal of the study is to take advantage of the proved STATCOM ability for injecting reactive current in order to mitigate the disconnection of large amounts of wind farms in case of severe grid faults. The proposed methodology was developed and tested in coordination with the Portuguese TSO and it is based on the formulation of an optimization problem in order to minimize the installed STATCOM power while ensuring its compliance with the current grid code requirements, namely in what concerns to the system stability and security. Given the discrete and complex nature of the problem, a hybrid approach, combining both a heuristic method and an Evolutionary Particle Swarm Optimization (EPSO) algorithm was developed. Results show the effectiveness of the proposed methodology as well as its robustness regarding the validity of the obtained solutions while facing the most severe operational scenarios.

Index Terms-- EPSO, Fault Ride Through, Grid Code, STATCOM, System Security, Transient Stability, reactive current injection

1. INTRODUCTION

Over the last decade, different factors such as environmental concerns, political incentives and technological developments have contributed to a steady increase of the worldwide wind generation installed capacity. According to statistics of the Global Wind Energy Council, worldwide installed wind power increased from 17.4 GW at the end of the year 2000 to 318.1 GW by the end of 2013 [1]. Regarding the specific case of the Portuguese electric power system, the wind power installed capacity by the end of 2013 was around 4648 MW (excluding Madeira and Azores islands). This installed power accounted for about 24% of total electric energy consumption in that year [2]. According to the Portuguese TSO predictions for the next years, wind capacity will continue to rise, reaching more than 4700 MW until the end of 2014.

The massive presence of wind generation in electric power systems naturally displaces conventional units, thus increasing the risk of system security. Therefore system operators have been defining very restrict rules and conditions for allowing increasing wind power integration, which are generally referred as grid codes. Grid codes usually require that Wind Farms (WF) withstand several disturbances and have the capability to support network operation by providing some types of services. Recalling for international grid code requirements for wind power integration, Fault Ride-Through (FRT) capability and reactive current injection during voltage dips are usually mandatory requirements [3, 4].

In Portugal, the grid code entered into force only in 2010 [5]. Although WF with FRT are currently being widely adopted, a substantial percentage of WF were constructed and commissioned prior to the definition of the grid code. Despite the ongoing efforts for adapting the old WF to meet the new requirements, the amount of non-FRT compliant WF may lead to significant amounts of generation tripping in case of grid faults, which can compromise system security.

Continuous adaptation of non-FRT compliant WF is thus a key objective defined in the Portuguese grid code in order to improve overall system security. Also, it is from the responsibility of the WF promoter to take the necessary measures in order to comply with the grid code requirements. In order to achieve this goal, there are generally two strategies that can be exploited. The first strategy may involve refurbishment of existing WF, which can be very expensive in the case of the oldest ones. The second strategy includes the installation of external solutions at the WF or at individual turbine level. In this case, studies for the proper sizing of the solution are oriented to improve the dynamic behaviour of a single WF through the use of FACTS devices based on series or parallel compensation (such as Dynamic Voltage Restorers – DVR and STATCOM or SVC, respectively) [6-8]. In this case, studies just consider the local impact of FACTS installation and do not analyse the system-level impact of the FACTS siting and sizing. Therefore, advanced methodologies for dealing with the problem of FACTS sizing and location are not required.

Nevertheless, technical solutions for the adaptation of existing WF (WF existing at the time of grid code publication) in order to be compliant with new requirements defined in the grid code may not be adopted by WF promoters in Portugal if the promoters are able to demonstrate that it is not economically feasible to do the necessary adaptions [9]. Therefore, the Transmission System Operator (TSO), as the entity liable for assuring global system security, has to identify appropriate mechanisms to mitigate the resulting effects from generation tripping following grid faults. This is a critical condition in the transmission system and is presented within the framework of the current Portuguese grid code, which specifies that the system should be transiently stable and in case of severe disturbances should not experiment simultaneous generation tripping larger than 2000 MW in the Portuguese control area [5]. At the TSO level, one possible complementary solution to mitigate this problem could rely on the location and sizing of FACTS devices to provide additional voltage support during grid faults and avoid large amounts of undervoltage WF tripping. Regarding this specific issue, STATCOM devices clearly stand out regarding voltage support during voltage dips when compared to other FACTS technologies [7].

While following this conceptualisation for identifying a proper solution, in [10] the authors proposed a trial and error approach that illustrates the possibility of improving the security of the Portuguese transmission system through the use of STATCOM based solutions. However, the authors do not consider multiple scenarios and multiple fault conditions. In a recent study [11], several operational conditions of the Portuguese transmission system were taken in consideration for a preliminary assessment of possible STATCOM based solutions regarding the aforementioned objectives. Nevertheless, a systematic methodology and full scale validation of the solutions are not addressed.

The use of methodologies based on meta-heuristic for finding the optimal placement and the size of FACTS devices have been addressed with different goals: improve transient stability margin [12-14], improvement of voltage profiles and reduce losses [15, 16] or increase total transfer capability [17-19]. However, neither the solutions were oriented to the improvement of system security due to the loss of large amounts of wind generation, nor were designed over real transmission systems. Furthermore, the optimized solutions are requested to respond to long term related problems (steady-state operation), not addressing the dynamic response of the electrical system.

In this sense, this paper presents the development of an innovative methodology regarding the need of the Portuguese TSO for sizing and locating STATCOM devices in the Portuguese transmission system through the assessment of the system global transient stability and post-fault system conditions. Within this current framework, the TSO will be the owner and the sole responsible for the operation, control and maintenance of the new devices that will be installed on the grid. The proposed methodology was developed and validated in close coordination with the Portuguese TSO – REN (*Redes Energéticas Nacionais*). Such process required the quantification of the expected simultaneous generation tripping according to grid code requirements, while considering robustness issues through the consideration of several operational scenarios. The problem was tackled by the use of a hybrid optimization algorithm, which combines an enhanced Evolutionary Particle Swarm Optimization algorithm (EPSO) and a heuristic procedure for finding the optimal locations of the devices and achieves their minimal nominal capacity. Several possible operational scenarios, FRT capability level scenarios, and also a large set of severe faults were evaluated under dynamic studies, being the results computed under different perspectives in order to demonstrate the effectiveness of the proposed approach.

2. Characterization of the Portuguese Transmission Network

In this section, a brief presentation of the Portuguese transmission network is given, together with the characterization of the operational scenarios that were considered within the scope of this study. Those scenarios were later considered to validate the proposed methodology.

2.1. Electrical Network

The Portuguese transmission system comprises the 400 kV, 220 kV and 150 kV voltage levels. The link between the transmission and the distribution grid is done at Substations (SS) with the 63 kV voltage level. In these type of substations, the 63 kV busbars and related equipment also belong to the TSO (the distribution operator is only responsible for the 63 kV feeders connected to these king of substations). Regarding WF installed in the Portuguese electric power system, it is important to mention that some of them are connected to the highest voltage levels of the system, but a significant percentage are connected to the distribution grid in substations belonging to the distribution system operator. However, regardless the connection point (distribution or transmission system), all of them should comply with the grid code requirements.

The Portuguese electric power system has a strong mix between (conventional) thermal and hydro power plants, while comprising also strong interconnections with Spain. For that reason, it is a usual practice to consider the complete Iberian transmission system model in several types of studies, as it is the case of the work presented in this paper. French and Moroccan transmission systems, also connected to the Iberian system, were represented through their equivalent models at the correspondent interconnection points. The Iberian system have been modelled in the PSS/E simulation package (version 32), using several user-defined models as well as PSS/E library models.

2.2. Grid Operational Scenarios

Taking into account the TSO point of view, a set of operational scenarios was defined as the most representative ones. Scenarios selection has in consideration peak and valley power load levels, the relevance of the hydro power production (through the consideration of wet and dry scenarios) and the power import/export levels with the Spanish system. Given the Portuguese grid code requirements, scenarios with a high share of wind power integration have also very high relevance. Consequently, the following set of scenarios were defined by the TSO and fully modelled in PSS/E: Wet Winter Peak Load (WWPL), Dry Winter Peak Load (DWPL), Wet Summer Peak Load (WSPL), Dry Summer Peak Load (DSPL), Dry Summer Valley Load (DSVL), Dry Summer Valley Load with low wind power (DSVL_W30%) and Dry Winter Valley Load with low wind power (DWVL_W30%). All peak load scenarios as well as the DSVL scenario are characterized by a high wind power injection, corresponding to approximately 80% of the installed wind capacity. The others two valley load scenarios are characterized by having a relative low wind power injection, representing approximately 30% of the total installed wind capacity in Portugal and zero power exchange with the Spanish system. A general characterization of the Portuguese transmission system generation, including the interchanges with the Spanish system in the referred scenarios is depicted in Table I (conventional generation includes thermal and hydro units as well as mini-hydros and co-generation units). Generation units connected the distribution grid are represented by the TSO as equivalent generators in the 63 kV busbar of the SS connected to the transmission grid.

Table I - General Characterization of Operational Scenarios under Study in the Portuguese Transmission System

	Grid Scenarios						
	WWPL	**DWPL**	**WSPL**	**DSPL**	**DSVL**	**DSVL_W30**	**DWVL_W30**
Total Load (MW)	10340	10340	8666	8666	6134	6134	6362
Conventional Generation (MW)	2581	8738	2053	7048	1813	4318	4477
Wind Generation (MW)	5136	5136	5136	5136	5136	1926	1926
Total Generation (Portuguese Network)	7717	13873	7189	12183	6948	6243	6403
Exported (+) or Imported (-) Power (MW)	2900 (-)	3250 (+)	1700 (-)	3250 (+)	600 (+)	0	0

Regarding WF installed in Portugal, it was also provided by the TSO a detailed characterization of the FRT compliance per WF (in the studied scenarios only about 50 % of the total WF installed capacity are compliant with the current Portuguese grid code requirements). WF not FRT compliant are set to instantaneous undervoltage tripping at 0.85 p.u.. Regarding the Spanish transmission system, it is assumed that all WF are fully compliant with current Spanish grid codes in terms of FRT capability and reactive current injection during voltage sags in all the studied scenarios [20].

2.3. Wind Generation and STATCOM Modelling

Special attention was given to the modelling of wind generation in the Portuguese transmission grid, since FRT capability is crucial for the evaluation of system security in case of severe faults. For recently build WF simulation models provided by the manufacturers were used. For the other ones, a general user defined WF model was used [21], whose main characteristic is the ability to easily model reactive current injection capability and of the voltage versus time curve associated to the FRT requirements [5]. Regarding the reactive current injection capability of the WF following a fault, typical time-delays were considered to represent the behaviour of the different WF. These time delays were provided by the TSO and are correspond to two values: 80 ms and 120 ms.

With respect to Spanish wind generation, PSS/E model "WT4" was adopted. An undervoltage tripping relay (PSS/E built-in model "VTGTPA") was also added to each Spanish WF and parameterized accordingly to the Spanish grid code regarding FRT requirements [20].

The STATCOM devices were modelled using the "CSTCNT" model available in PSS/E libraries [22], which is capable of accurately representing the dynamic behaviour of this kind of device.

2.4. Transmission Grid Security Criteria

From a security point of view, the Portuguese grid code specifies that the transmission system should be transiently stable for different types of faults when cleared either by the main protection (first operating level) or backup protections (breaker failure or a tele-protection system failure – second operating level). Additionally, the grid code specifies, in its planning criteria, that in case of severe disturbances the Portuguese system cannot admit the simultaneous tripping of more than 2000 MW.

3. Methodology for Siting and Sizing STATCOM Devices in the Transmission Grid

The developed methodology for siting and sizing STATCOM devices at the transmission network comprises the resolution of an optimization problem, whose main goal is the identification of the less costly and the most robust solution regarding the number of worst case scenarios and possible fault locations for which it should be validated. Following this principle, Fig. 1 presents a flowchart depicting the main steps of the developed methodology. As can be seen, TSO assumes some crucial functions in the context of such a methodology, specifically regarding the definition of grid operational scenarios, FRT characterization at individual WF and validation of network components models to be used in simulations (namely wind farms machines models). Over the next sub-sections important aspects of the steps which defining the methodology presented in Fig. 1 are discussed.

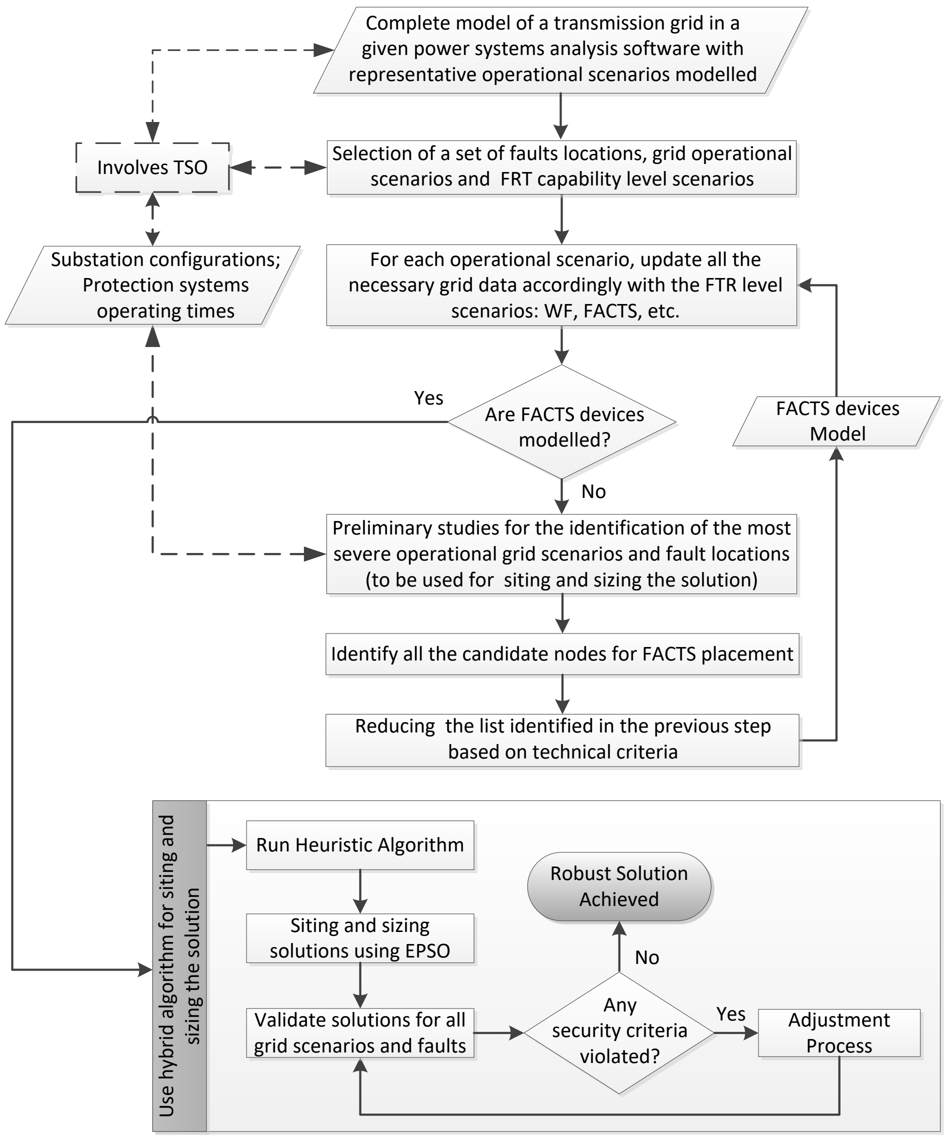

Fig. 1. Flowchart of the proposed methodology

3.1 Identification of the Most Severe Faults and Grid Operational Scenarios

When dealing with a large number of possible faults and operational scenarios, it is possible to have some redundancy. However, it is quite important to limit the number of dynamic simulations to a feasible number. On the other hand, it is also important to assure the final solution to be robust and technically effective for any fault or operational scenario that might occur during the operation of the transmission grid. In order to assure this situation, a worst case scenario approach is followed.

In this sense, one of the first steps of the proposed methodology involves a meticulous identification and selection of a set of the most representative fault locations and grid operational scenarios among the available candidates. This process was developed in close collaboration with the TSO. Based on TSO information, a set of the most critical faults location were identified. Subsequently it was followed by the detailed characterization of the circuits in which those faults may occur, as well as the associated SS configuration and protection systems clearing times, considering both normal protection operation and protection failure. Over the Portuguese transmission system, a total of 22 faults locations (9 at 220 kV level and 13 at 400 kV), were considered by Portuguese TSO as the most severe ones. The identification of fault locations has in consideration the relevance of the SS, given by its short-circuit power, as well as the electric proximity to WF.

The next step consists on the simulation, for the complete list of the previously identified fault locations and for all grid operational scenarios, three-phase short-circuits in each SS circuit. Simulated faults consisted on the simulation of a barker failure and a tele-protection system failure, since these are the most severe fault conditions regarding system transient stability.

In Fig. 2 it is possible to have an overview about the geographical location of the most severe faults as well as the most significant areas in terms of WF concentration. In the selection of the most severe faults a worst case approach was followed by taking into consideration the transmission grid stability conditions previously defined (see section 2.4). Table II provides a characterization of the transmission system SS where the most severe faults were identified. The table includes also information on the protection times adopted to simulate normal protection actions (first operating level - T1) as well as tele-protection failures and breaker failures (second operating levels - T2), the SS configuration and the number of circuits connected to the SS. The SS configuration has a strong importance and is required to be taken in consideration in the simulations because they influence the way how a fault is eliminated and the post-fault system state regarding line outages.

Table II- Characterization of SS where the 5 critical faults are simulated

Substation	SS Configuration	No of Circuits	Breaker Operating Times		Tele-protection Operating Times	
			T1 (ms)	T2 (ms)	T1 (ms)	T2 (ms)
1 (400 kV)	Double bus bar	9	80	190	80	340
2 (400 kV)	Breaker and a half	6	80	190	80	440
3 (400 kV)	Breaker and a half	10	80	190	80	340
4 (400 kV)	Double bus bar	8	100	250	100	350
5 (400 kV)	Breaker and a half	9	100	250	100	350

Afterwards, a full dynamic characterization of the two types of faults in each SS circuit in order to get a detailed overview of the resulting impact on the network. From such results, the worst case fault location and circuit are selected. A smaller group of operational scenarios and correspondent faults is chosen for siting and sizing proposes, being the other ones used to evaluate solution's robustness. According to the grid security criteria that should be considered (defined in section 2.4), the identification of a solution should be fully oriented to the worst case scenarios regarding the issue of simultaneous generation tripping. However, it is also desirable, from a robustness point of view, to evaluate the effect of the identified solutions for other scenarios and fault conditions.

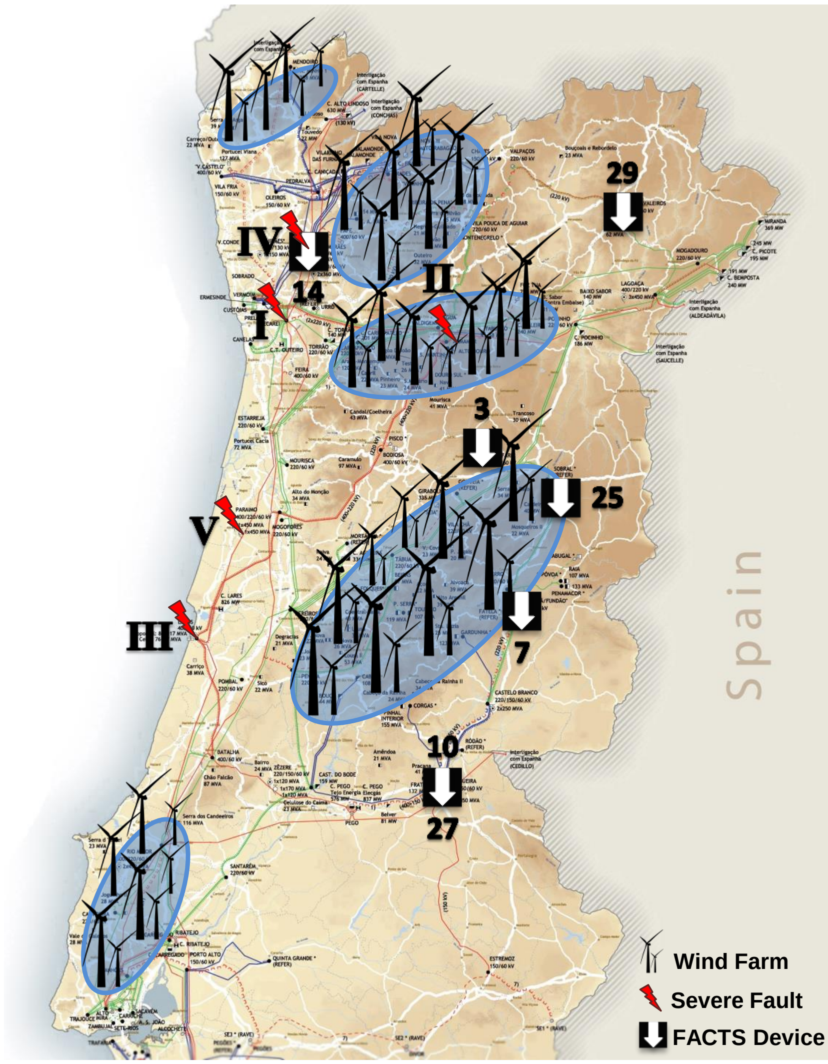

Fig. 2 - Portuguese Transmission System: location of the most severe faults, major areas of WF concentration and location of STATCOM devices to support system operation

3.2 Initial Selection of Candidate Nodes for STATCOM Placement

In the Portuguese electric power system the majority of medium and small WF are located within the distribution grid, and therefore located out of the TSO domain. Conversely, it is also possible to find large WF (in the 100 MW range) directly connected to the very high voltage grid. Previous studies related to the use of STATCOM devices to improve FRT conditions in WF demonstrate that this devices are more effective regarding FRT capability enhancement when placed closer to the WF connection point [6, 7]. Considering the scope of this study and the domain of responsibility of the TSO, the following technical considerations can be defined regarding the initial definition of candidate nodes for installing STATCOM devices:

- From an economical view point it will not be effective to consider the installation of STATCOM devices in SS where the total WF installed power is below a certain limit. In this study the most appropriated limit was considered to be 20 MW.

- Regarding the WF installed in the distribution grid level, STATCOM devices must be connected as closer as possible to the WF (in this case, the limit is the 63 kV busbar of the transmission SS providing interface to the distribution grid).

- Relevant information regarding voltage sag profiles at WF without FRT capability can be extracted from the dynamic simulations related to faults that were previously identified. At this stage, some candidate nodes for STATCOM installation can be excluded if the minimum voltage value observed at their connection point stays below a certain limit during the fault. In this study the value of 0.6 p.u. was considered. The general idea associated to such selection is related to the fact that a STATCOM is not able to sustain the terminal voltage of a WF without FRT above 0.85 p.u. (undervoltage tripping limit) if it is prone to suffer very severe voltage dips during a fault.

3.3 Optimization Problem Definition

In general terms, the optimization problem to be addressed deals with minimizing the total cost of installed STATCOM devices, while assuring that the transmission system complies with the security conditions defined in section 2.4. From a technical point of view, the cost is directly related to the total installed STATCOM capacity, being neglected installation and operation costs. In this sense, the optimization procedure is carried out individually for each *i-th* operational scenario and simultaneously to a set of faults *h* over that scenario according to:

$$\text{minimize} \quad f^i = \sum_{j=1}^{N} u_j^i * S_j^i \tag{1}$$

subject to

$$u_j^i \in \{0;1\} \tag{2}$$

$$S_{j,\min}^i \le S_j^i \le S_{j,\max}^i \tag{3}$$

$$SGT_h^i < 2000\, MW \tag{4}$$

$$SGT_h^i = WGT_h^i + SyGT_h^i \tag{5}$$

where f^i is the objective function that characterizes the total STATCOM installed power for the operational scenario *i*, S_i^j is the installed power of a STATCOM device located at node *j* in the operational scenario *i*, u_i^j is a binary decision variable reflecting the decision of installing a STATCOM in node *j*, *N* is the total number of possible node locations for STATCOM devices, SGT_h^i is the simultaneous generation tripping (MW), WGT_h^i is the wind power generation tripping (MW) and WGT_h^i is the conventional generation tripping due to loss of synchronism (MW), respectively for the operational scenario *i* and fault condition *h*. Due to the problem complexity, the optimization procedure is selected to run for each operational scenario individually, being later established a procedure to harmonize the solutions and guarantee its robustness among several operational scenarios.

3.4 Finding the Solution through a Meta-Heuristic Algorithm

To handle the optimization problem formulated above, a hybrid approach, combining a meta-heuristic algorithm and a heuristic procedure was used. The meta-heuristic optimization algorithm is the base method for solving the siting and sizing problem, while the heuristic procedure is aimed to enhance the optimization process efficiency by providing inputs to the meta-heuristic. The heuristic method is explained in the following section.

The Evolutionary Particle Swarm Optimization (EPSO) [23] is used as the meta-heuristic algorithm. This tool has been used with success in several scientific studies related to power systems [24-26]. The EPSO fitness function relies on the output of transmission system dynamic simulations to evaluate the feasibility of a given solution.

The device siting problem is discrete which makes the problem challenging, mainly since it leads to a mixed-integer formulation and binary variables. In order to overcome this situation, the discrete nature of the problem was modelled as follows: when the algorithm sites a STATCOM device with nominal capacity below a specified value (e.g. less than 10 MVAr), then this STATCOM device is not considered as a feasible solution in a dynamic simulation.

3.5 The Need for Integrating an Heuristic Procedure

Typically, the EPSO algorithm initiates the optimal solution search by randomly generating a population of solutions as a set of randomly chosen points within an *n*-dimensional space where (*n* is the number of variables composing the EPSO solution). In this case, problem dimension corresponds to binary decision variables weather to install or not a STATCOM device in a particular location and continuous sizing decision variables related to the device nominal power. However, reducing the dimensionality of EPSO search space is beneficial in terms of computational efficiency. In order to make this procedure effective in this specific case, it is necessary to provide an initial delimitation of the search space, thus requiring the definition of potentially good candidate locations for the STATCOM devices, as well as limits regarding the device nominal power. In order to achieve these goals, a specific procedure was implemented, as explained next.

For a given WF without FRT, the capacity of avoiding undervoltage tripping during a short circuit will result mainly from the additional voltage support provided by the STATCOM devices located closer to that WF. Having in mind this fact, a heuristic procedure based on engineering criteria was developed. The main feature of this process is that it allows the individual characterization and evaluation of the STATCOM based solutions with the highest potential to prevent the tripping of WF located nearby. This makes possible to reduce the number of solutions to be found by the meta-heuristic as well as defining nominal power ranges for each FACTS device individually (speeding up the optimization process).

From a practical point of view, the method consists on an iterative process that assumes a certain operational scenario i and a critical fault condition h, being developed as follows (see Fig. 3):

1) Assume the installation of a STATCOM device in a candidate node j (according to the conditions defined in section 3.2);
2) Start an iterative procedure consisting on the step increase of the nominal power of the STATCOM device in order to define the associated power that avoids the undervoltage tripping of the WF connected to the same node;
3) Evaluate the quality of this initial sizing of the STATCOM device by a ratio factor given by the quotient between the WF power in node j whose undervoltage tripping is avoided ($P^{i}_{WF,j}$) and the nominal power of the STATCOM device that assures these condition ($S_{i,j}^{h}$): $\lambda_{i,j}^{h}=P^{i}_{WF,j}/S_{i,j}^{h}$;
4) Proceed to the next candidate node and return to step 2);
5) After evaluating all candidate nodes for each fault condition, order of the initial sizing of the solutions according to the best ratio $\lambda_{i,j}^{h}$.

This procedure is extremely effective at this stage, since the mutual effects of several STATCOM devices connected in the grid are initially neglected. Nevertheless, these mutual effects are taken into account in the subsequent phase through the refinement of the optimization process based on the use of a meta-heuristic (EPSO algorithm). As a result, the order in which the candidate nodes are evaluated in this procedure is not as matter of concern, since a final ordering is produced afterwards. At the end of this process, the best candidates to be considered within the meta-heuristic procedure are selected from the ordered lists of candidates that were organized for each critical fault condition.

3.6 Solution Adjustment Process Towards Robustness

The solution adjustment process is a procedure to run after achieving optimum solutions for each operational scenario initially selected for siting and sizing purposes and is intended to assure robustness for all the operational scenarios. This process is of utmost importance since solutions are initially sized for a single operational scenario at a time and may be not effective for another operational scenario. In this case, the proposed adjustment process consists on a sequence of steps detailed below:

1) Run a dynamic simulation for specific faults over an operational scenario and for a certain solution (not initially sized for that scenario).
2) Evaluate the minimum voltage profile recorded at WF without FRT that are associated with grid nodes identified as candidates for the installation of STATCOM devices.

3) Identify the WF power whose undervoltage tripping must be avoided to ensure that all transmission grid security criteria are met. Considering the minimum voltage registered at WF that trip during the fault, identify and chose those with the greatest potential for avoiding undervoltage tripping (lower voltage close to 0.85 p.u.).

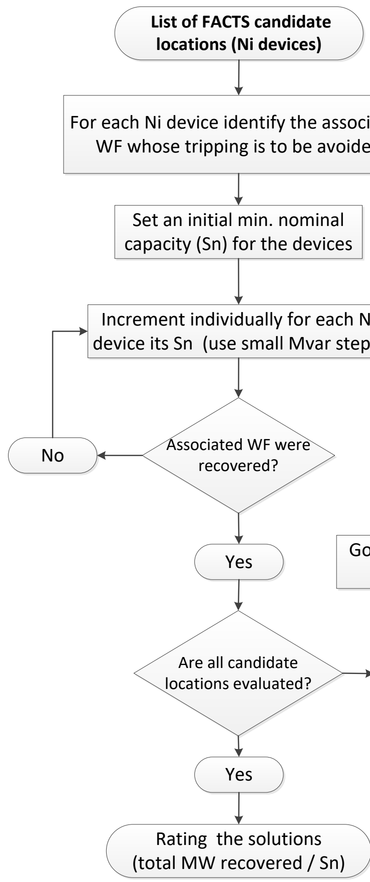

Fig. 3 - Illustrative flowchart of the heuristic procedure

4) Increase nominal capacity of the STATCOM device closer to those WF up to a value that avoids its undervoltage tripping. Initially, the increments are performed over STATCOM devices already sized and located in the solution under consideration. If there are no devices in these conditions, or if more are required, new devices are located and sized taking into account the locations with the greatest potential for recovering the WF identified in step 3).

5) Validate the new solution (and test the possibility of reducing STATCOM nominal power) by considering the mutual effects between all the units to be connected to the grid. In this process small adjustments should be performed individually on all devices in an attempt to minimize its nominal power capacity.

6) Validate the obtained solution for the complete list of severe faults to be considered in the operational scenario under analysis. In a first instance solutions adjustment is performed for the more severe faults. Therefore, it is expected that the solution might be also robust in the other faults. Whenever such situation does not occur,

repeat steps 1) to 5) for faults that have led to violations of the established criteria.

4. Results and Analysis

Following the presentation and discussion of the proposed methodology for sizing and siting the STATCOM devices in the Portuguese transmission system, this section shows the most important results that were attained. For a better understanding, results were divided in three groups: characterization of the simulated situation, siting and sizing the solutions and sensitivity studies.

4.1. Characterization of the Simulated Situation

Fig. 4 evidences the simultaneous generation tripping in the available operational scenarios and considering the most severe grid faults involving breaker and teleprotection system failure (according to Table II). The simultaneous generation tripping accounts for both WF and conventional generation tripping.

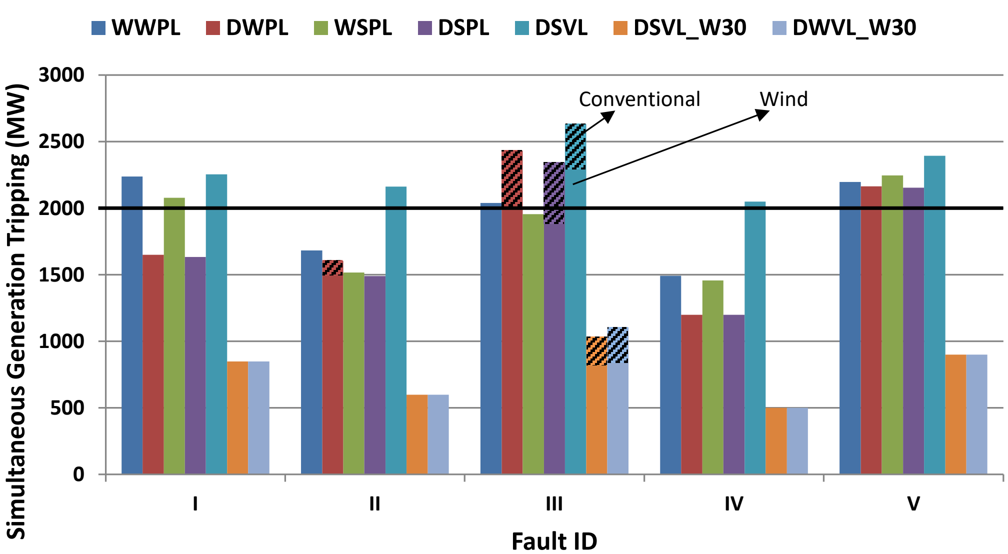

Fig. 4 - Simultaneous generation tripping

The obtained results clearly put in evidence that 5 of the operational scenarios considered in the study revealed violation of grid stability criterion related to the simultaneous generation tripping. In particular, the DSVL scenario can be easily recognized as the most critical operational scenario, where 5 different fault locations are leading to huge violations of that criterion. Thus, this scenario was the only one selected for siting and sizing the solution.

In order to evaluate the behaviour of the system following the normal operation of the protections systems, Fig. 5 provides a comparison of the simultaneous generation tripping considering Backup Protection Operation (BPO) and the Normal Protection Operation (NPO). As it can be observed, system security is also at risk due WF that trips in the first moments following a short-circuit occurrence. This finding proves that, from the technical point of view, the installation of STATCOM devices could be important even for the case where protection system operates in normal conditions.

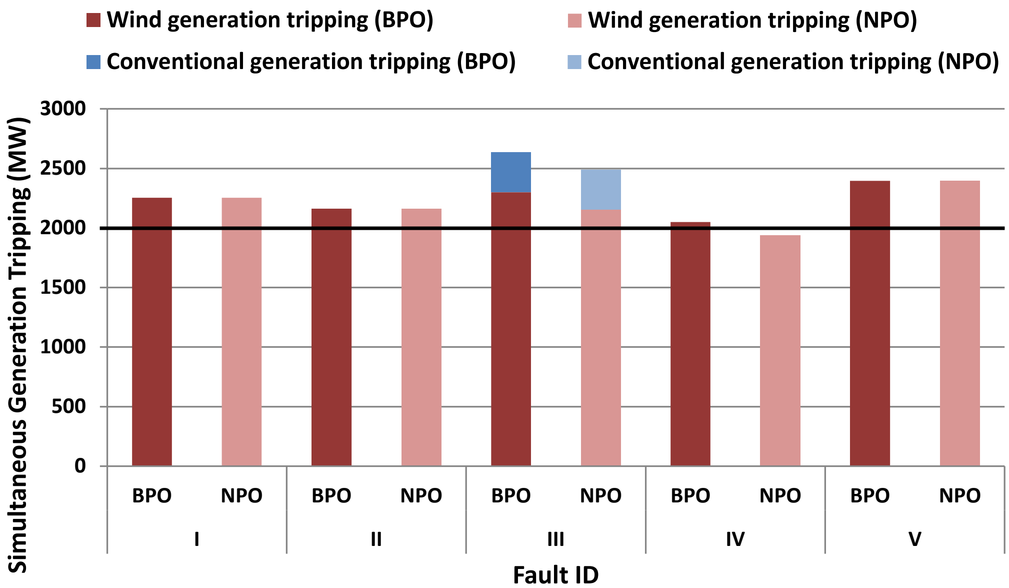

Fig. 5 - Comparison between cases with and without protection failure

4.2. Sizing and Siting the Solution

The analysis of the most severe faults with respect to system impact led to the identification of 3 different fault locations for solution siting and sizing in the DSVL scenario (fault ID No. 1, 3 and 5). With respect to the locations for the installation of STATCOM devices, a universe of 81 initial candidate locations was identified. Then, filtering those locations in accordance to the conditions established in section 3.2, a more reduced list composed by a total of 29 possible STATCOM location have been achieved for the operational scenario under study. Afterwards, the heuristic process execution (according to Fig. 3) allowed to selected only 15 locations, which were found as "good" candidates for STATCOM placement (in this case, it was considered that good initial solutions are the ones with $\lambda_{i,j}^{h}$ >1). This list was used to set the space of the solutions where EPSO algorithm searched for optimal solution. Therefore, the dimension of the *n*-dimensional space for the ESPO algorithm is n=15.

Table III presents results for the final solution found after solving the optimization problem using an EPSO based algorithm. As can it be seen, the solution is composed by 7 STATCOM devices, which are required to be installed in 6 different transmission system SS (resulting on a total nominal capacity of 556 MVAr. STATCOM devices with ID no. 10 e 27 are connected to the very high voltage and high voltage sides of a 150 kV/63 kV SS, respectively. This SS has large WF connected to both voltage levels, which justifies the use of different STATCOM devices to avoid the tripping of the correspondent WF.

A perspective of the geographical location of the STATCOM devices on the Portuguese transmission system is presented in Fig. 2. As it can be observed, devices are preferentially located in nodes electrically distant to the most severe fault locations and predominantly at the lower voltage side of the correspondent SS. The solution identified for the DSVL scenario was then evaluated for the other available operational scenarios in order to check for its robustness. As it can be observed in Fig. 6, the solution is robust in all operational scenarios and faults under analysis. Consequently, in this specific case, adjustment process of the solutions was not necessary to be executed.

Table III - Final solution characterization

STATCOM ID	Voltage (kV)	Sn (MVAr)
3	63	54
7	220	117
10	150	188
14	150	127
25	63	10
27	63	40
29	63	20
Total		556

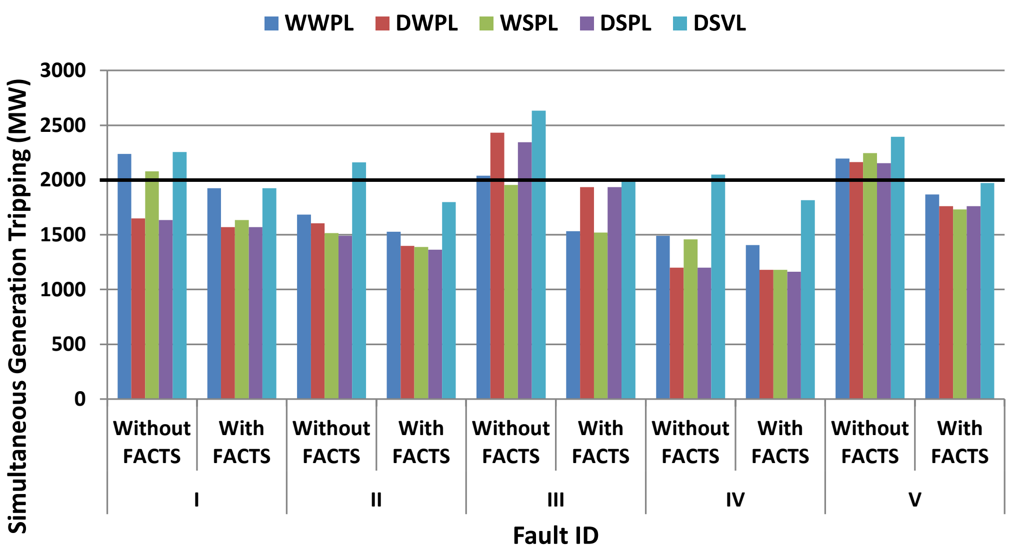

Fig. 6 - Impact of the sized solution on the amount of simultaneous generation tripping

However, as it can be seen in Fig. 6, the solution is able to provide significant margins regarding simultaneous generation tripping criterion in the other scenarios. Thus, the proposed methodology was applied not considering the DSVL scenario. The main goal was to observe how different generation profiles (namely peak load scenarios) influence the siting and sizing of STATCOM devices. In these circumstances, both WWPL and DWPL scenarios were selected. Following the same sequence of methodological steps and assumptions as done for DSVL, the solutions found with the EPSO algorithm on those scenarios were verified as non-robust in the other scenarios and faults selected at the validation stage. Thus, it was necessary to apply the adjustment process. Final results are presented in Table IV. As can be seen, one of the two initial solutions (obtained from the EPSO algorithm) comprises a total nominal capacity of 173 MVAr to be robust in the

WWPL scenario and the other a total of 191 MVAr to be robust in the DWPL scenario. A robust solution for those two scenarios requires a total nominal capacity of 304 MVAr. After running the adjustment process, the final solution requires a total of 319 MVAr to be valid for all the faults and operational scenarios (a value far below of the one obtained when the severe scenario DSVL is considered).

Comparing Tables III and IV, the influence of the different operational conditions on the obtained results is notorious. The additional generation exiting in peak load scenarios requires less grid voltage support from STATCOM devices in order to ensure the grid security criteria (about 40% reduction in STATCOM total installed capacity).

Table IV - Results of the a STATCOM based solution not considering the DSVL scenario

STATCOM ID	Sn WWPL (MVAr)	Sn DWPL (MVAr)	Sn WWPL & DWPL (MVAr)	Sn robust for both scenarios (MVAr)
3 (63 kV)	37	18	18	**0**
6 (63 kV)	0	9	0	**0**
7 (220 kV)	26	48	60	**60**
10 (150 kV)	110	0	110	**140**
17 (63 kV)	0	30	30	**30**
22 (63 kV)	0	49	49	**49**
23 (63 kV)	0	37	37	**40**
Total	173	191	304	**319**

4.3. Sensitivity Studies

In order to quantify the minimum degree of WF with FRT necessary to avoid the violation of the maximum simultaneous generation tripping criteria, an additional study was conducted in collaboration with the TSO, which defined two different sets of WF that should become FRT compliant (and leading to a total WF being FRT of about 60% and 65 % of the installed capacity). Fig. 7 depicts the simultaneous generation tripping for these additional conditions. As it can be observed, the increase of WF being FRT compliant to a value between 60% and 65% will make possible to meet all the defined security criteria without the need of other type of additional measures. The results in some of the scenarios for a FRT level of 65% are not presented because the security criteria had been already met considering FRT capability level of 60%.

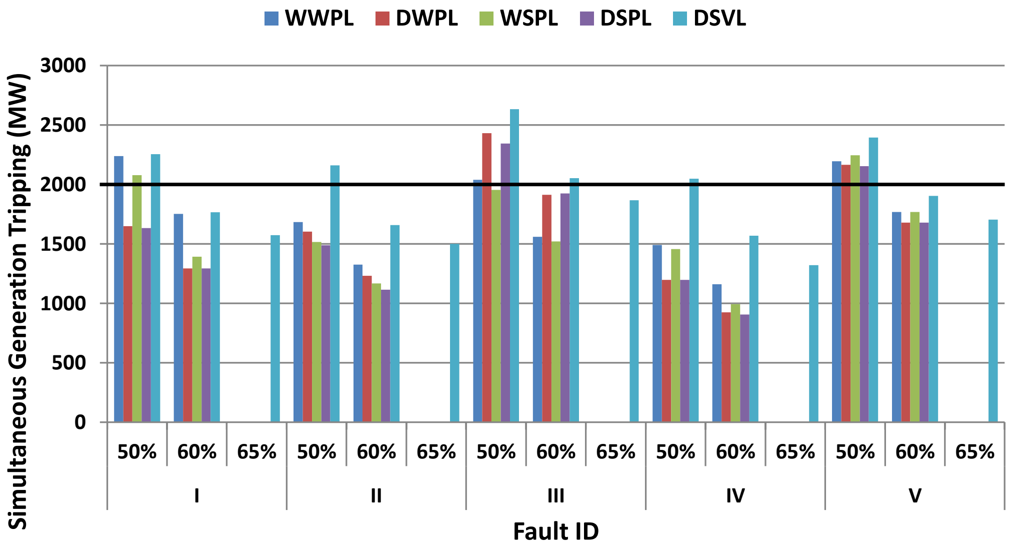

Fig. 7 – Simultaneous generation tripping for each operational scenario depending on FRT capability levels

5. Conclusions

This paper presents and discusses a methodology developed in coordination with the Portuguese TSO for dealing with the problem of siting and sizing STATCOM devices in the transmission grid in order to improve security conditions. The proposed methodology allows the identification of the most technical-effective and robust solutions for avoiding violations of the security criteria regulated in the actual Portuguese transmission grid code, namely regarding the maximum simultaneous generation tripping criteria.

The obtained results demonstrates that STATCOM devices are effective solutions to provide voltage support during network faults and avoid undervoltage WF tripping. The final solutions that were obtained are demonstrated to be robust in several operational scenarios and for the most severe grid faults.

Finally, it is important to stress that in order to proceed towards a final implementation of the solutions, an exhaustive economic analysis (cost-benefit analysis) and terrain feasibility evaluation must be conducted by the TSO (for example, in what concerns SS expansion to accommodate STATCOM devices). In a case where additional constrains result from these type of evaluations, the proposed methodology can be used in order to re-size the solutions.

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