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Load Shedding – Coordination between the Portuguese Transmission Grid and the Distribution Grid with Minimization of Loss of Distributed Generation

Ricardo V. Fernandes, Susana A. B. de Almeida, Fernando P. Maciel Barbosa and Rui Pestana

Abstract—**Nowadays the total sum of Distributed Generation (DG) in the Portuguese Distribution Network (DN) is extremely significant. Previously, load shedding schemes were designed without taking into consideration this type of generation. In this paper, the Portuguese Electrical System is studied through a static analysis using real data, and the new relay parameters to be applied in substations are evaluated, continuously bearing in mind the strict coordination with those of the DN. In order to achieve these purposes, an algorithm was developed to rank possible candidate substation feeders to the load shedding plan, using Ms Excel to process data and perform the calculations. The obtained results show that by using the designed algorithm it is possible to find a systematic process for determining under-frequency relay parameters considering the trade-off between shedding critical consumers and shedding DG.**

Index Terms—**Distribution Network, Distributed Generation, Load Shedding, Transmission System.**

I. INTRODUCTION

Electrical Power Systems (EPS) are planned and operated in such a way that given the occurrence of an incident that involves the breakdown of any grid element, the simultaneous failure of a double-circuit overhead line, or the failure of the largest generator in service, supply interruption (excluding single-feeding points without alternative) or permanent overloads shall never take place [1]. However, EPS are not designed to cope with severe disturbances that often imply loss of generation, causing the system frequency to vary.

Frequency in EPS is a system parameter that measures the balance between generation and demand plus losses. Thus, when an imbalance occurs, system frequency will change. In this paper, situations of frequency decline will be approached, as a result of the imbalance caused by the loss of a considerable amount of generation. If the system frequency reaches a defined threshold, it is of the utmost importance to resort to extraordinary measures in order to prevent aggravation and spreading of the disturbance. Therefore under frequency load shedding (UFLS) schemes are put into action, cutting a specified amount of load according to defined steps in order to restore the required system balance. The standards for automatic load-shedding are in accordance with Policy 5, as stated in [2].

Environmental concerns have instigated generation of electricity from renewable energy sources. Despite the individual contribution provided by the DG may be low, the total sum of these producers is currently significant. This type of generation is often connected in the high and medium voltage level of distribution networks together with loads in the same feeders. In case of generation loss, automatic shed of feeders with load and generation must be avoided, especially when the power produced is equal to or larger than the consumption [1]. To overtake this problem, load shedding relays must be installed in the DN as close as possible to the consumers, increasing the efficiency of the load shedding plan.

The Portuguese Transmission System Operator (TSO) has the responsibility before UCTE to maintain the load shedding plan in accordance with the respective standards, rules and requirements. For this reason there are under-frequency relays installed not only in the DN, but also in the 60 kV level bays, which are propriety of the Transmission Grid, acting as backup relays, in order to guarantee that the adequate amount of load is shed when needed.

References [6]-[8] describe a practical example of under frequency load shedding action to control an emergency situation in the UCTE interconnected system, which occurred in November 4th, 2006. A serious system disturbance originated from the North German transmission grid affected the interconnected power systems of the UCTE synchronous area. After the tripping of many high voltage lines the UCTE grid was divided into three areas (West, North East and South East). This resulted in significant power imbalances and frequency deviations in each area [8]. The power generation loss in the Western area invoked a quick frequency drop, as

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can be seen in fig. 1, which resulted on the automatic activation of the defence plans [6]. Despite the success in preventing a major blackout, some flaws were identified, especially related to the loss of DG.

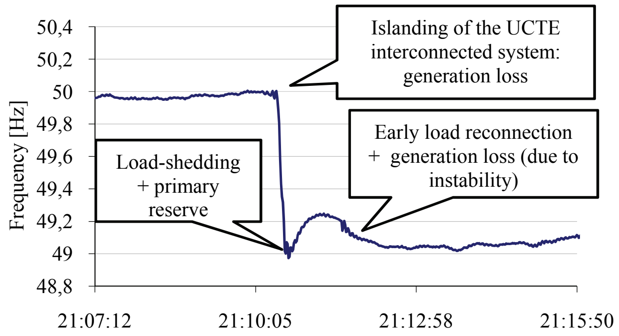

Fig. 1. Frequency evolution in the Western UCTE area before and after the disturbance (GMT) [7].

In this paper the amount of DG connected to the DN is considered for the load shedding plan, from the Portuguese Transmission Grid's perspective, aiming to minimize the loss of embedded generation and also to avoid shedding critical consumers. Due to this an algorithm was developed to rank possible candidate substation feeders to the load shedding plan, using Ms Excel to process data and perform calculations. The values used in the analysis are based on real data provided by the Portuguese TSO (REN) and by the Distribution System Operator (EDP Distribuição).

The Portuguese Electrical System was studied through a comparative analysis of different possibilities for the load shedding plan. The relay parameters to be applied in REN's substations are also evaluated, bearing in mind the strict coordination with the ones installed in the DN. Three study cases are compared with the actual load-shedding plan and the obtained results show that by using the designed algorithm it is possible to find a systematic process for determining under-frequency relay parameters, considering the trade-off between shedding critical consumers and shedding Distributed Generation.

The rate of the installed power regarding DG is increasing almost every day. Hence, there is a need to redefine the relay parameters, considering the DG as well as the relative importance of the load connected to each feeder.

II. Load-Shedding

In any electrical system there are always frequency deviations inside an acceptable range, but variations of higher magnitude may force the system to leave the normal state of operation. Frequency drops in the electrical system may occur after:

- Disturbance affecting generation units
- Incident in the electrical network
- Sudden load growth

The first two reasons are the main responsible for major frequency drops. In order to cope with these problems and avoid partial or total blackout of the EPS, it is imperative to have installed automatic devices for under-frequency load shedding.

A. UCTE Standards for Load Shedding Schemes

The Operation Handbook (OH) establishes the standards and guidelines for all TSOs regarding emergency actions facing harsh situations in Policy 5. Despite the following guidelines, the current policies allow each TSO to design its load-shedding plan. In the first synchronous zone of the UCTE, the instantaneous frequency must not fall below 49.2 Hz in response to a shortfall in generation capacity of 3000 MW. In that case, all TSOs are required to start shedding load at 49.0 Hz and to shut down running pumping storage units above that frequency as an operational measure [2]. The current Policies are not specific regarding load shedding, although the forthcoming Policy 5 of the OH will be more detailed.

B. The existing Portuguese Scheme

The Portuguese TSO supervises not only the very high voltage levels (150, 220 and 400 kV) but also the 60 kV busbars and circuit-ends that link the feeders to the high voltage network of the DN, as depicted in fig. 2. Frequency relays should be preferably installed in the lower voltage levels, seeking to shed load and to avoid shedding DG. Therefore, and because the Portuguese TSO is responsible for the Portuguese load-shedding plan before UCTE, frequency relays are installed in the 60 kV bays of the TSO and, when redundant, they are intended to act as a backup of those installed in the DN. In the DN the relays are installed in the medium voltage level.

The existing UFLS scheme does not consider installing frequency relays in power transformers and shunt capacitors bays as well as in generation feeders directly connected to the 60 kV of the transmission network. The same applies when the lower voltage circuit-end of power transformers is directly connected to the 60 kV busbar in the DN. The plan also considers automatic shut down of running pumping storage units at 49.5 Hz, although that amount of active power is not considered for the total sum of the shed load. All generation units must stay connected to the transmission system until 47.5 Hz.

The UFLS scheme has two frequency steps, at 49.0 Hz and 48.5 Hz, each shedding 25 % of the load. The total load shed by the existing plan sums up to 50 % of the EPS's load, which is the total synchronous demand registered in the previous year. The scheme is designed to cope with islanding of the Portuguese transmission system from the only existing neighbour, Spain, and thereby from the UCTE interconnected system.

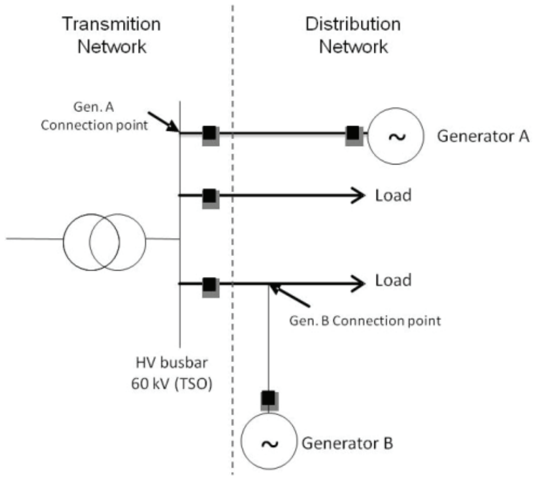

Fig. 2. Single diagram depicting the TSO and the DSO networks [1].

III. The Ranking Algorithm

The current UFLS scheme does not take into account the DG present in the DN. This paper presents a ranking algorithm that aims to provide the best feeder selection to be included in the UFLS scheme in order to guarantee that the goals in the existing scheme are met as well as the following goals by the presented order:

1. Minimize loss of DG
2. Minimize shed of priority demand

In addition, this paper also aims to assess the geographical distribution of the load shed.

A. Mathematical Formulation

The goal is to find a relation between the input variables in order to minimize the $\sum$ *loss of DG*. Minimizing this sum is equivalent to maximizing the load to be shed, i.e., when formulated as the difference between the power consumed (demand) and the power produced by DG in the same feeder, as showed in eq. (1). Therefore it is possible to consider the amount of DG connected to a specific feeder and to relate it with the amount of load and its priority. The expression that considers all the variables and the respective weights can be mathematically formulated as:

$$Maximize \sum_{i} \left(Load_i \times w_j - DG_i \times w_{DG} \right), \qquad (1)$$

where i is representing the feeder, w_j is the weight associated to the priority of load j, DG_i is the amount of DG connected to feeder i, and w_{DG} is the weight associated with the DG.

B. Load Priorities

Load priorities are defined by the DN operator. The Portuguese DN is divided into two different areas (North and South), each with its own regional DSO, thereby defining load priorities differently. As it can be observed from equation (1), the obtained results depend on load priorities. In order to apply the ranking algorithm, the use of an equal scale for load priorities is needed, independently of the regional DSO's scales. Load priorities are defined in a scale from 1 to 8 by the northern DSO and from 1 to 3 by the southern one, both representing 1 as the less priority loads and the others successively having more priority. To standardize load priorities, it was chosen to maintain the definition of 1 to 3, and to refer the northern DSO scale to these values, in accordance to the equivalences showed in TABLE I. Thus, priority 1 loads are the first to be shed.

Load priorities are defined by the DSO operator and consider whether or not the feeder connects to interruptible clients, to important clients both in HV and MV, to DG, and also consider the easiness of remote feeder reconnection after tripping.

TABLE I

Equivalence table for load priority standardization between both DSO

Load Priority	Standard Load Priority
1; 2	1
3; 4	2
5; 8	3

C. Weight definition and Sensitivity Analysis

To obtain the expected results, it is needed to define the weights of each input variable. These weights enforce that in the end the ranking results are compliant with the proposed goals.

For each load priority, a different weight was chosen to maintain the DSO criteria and to match the obtained results with the expected ones.

In order to apply equation (1), the reliability of the selected weights is crucial. Due to this fact, a sensitivity analysis is performed. In this analysis it is intended to check to what extent the final ranking is influenced by small changes in the weights, allowing to verify whether or not the results are coherent. Therefore a sensitivity analysis was done with different sets of weights, seeking for the limit values that change the final result. This approach allowed to choose the best set of weights.

D. Apply the ordered list to the UFLS scheme

The output of the ranking algorithm, with a specified set of weights, is an ordered list of the feeders. In order to assess the quality of the ordered list, and the set of weights used, it is then needed to design an UFLS scheme. The flowchart showed in Fig. 3 explains the process. It is a sequential process, executed step by step, until the final goal is met: shed 50 % of the total EPS consumption in two frequency steps, 25 % in each one, as referred in II.B. The first feeder in the list will be placed in the first frequency step. Then the second feeder in the list is also placed in the same frequency step if the threshold is not reached: to shed 25 % of the total load in the EPS. Until the amount of load to be shed is not met, the process repeats. Afterwards, the feeders are placed in the second frequency step, in the same way as done for the first frequency step. Then the UFLS scheme is completed when the sum of the load shed in the second frequency step is 25 % of the total EPS demand.

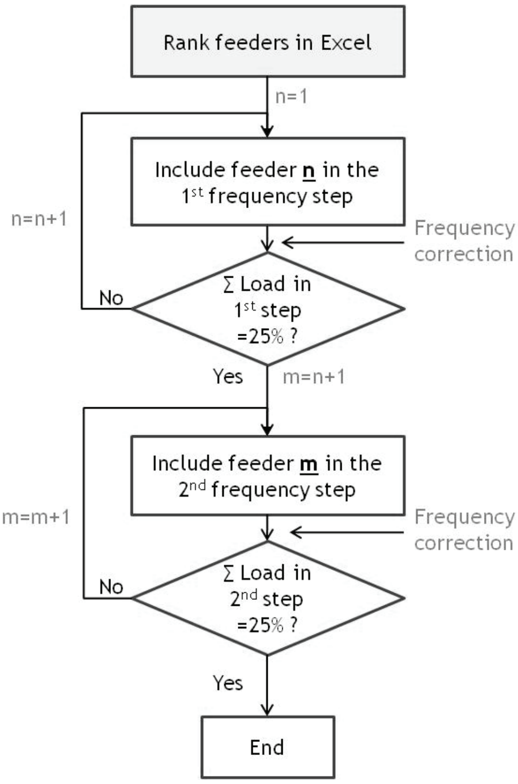

Fig. 3. Algorithm to design UFLS.

As previously mentioned, these frequency parameters are set into the relays installed in the TSO 60 kV bays, and when redundant, will act as backup of those installed in the DSO network. The frequency correction indicated in Fig. 3 helps to avoid overlapping the frequency settings of the DSO's relays with those of the TSO's. This will guarantee the coordination of the UFLS scheme between both operators. The frequency correction works in the following manner. If the frequency should be set in the 1st frequency step, at 49.0 Hz, then it must be changed to 48.8 Hz; if the frequency should be set in the 2nd step at 48.5 Hz, then it must be changed to 48.3 Hz. In case there are frequency relays installed both in the DN and in the transmission network for the same feeder, the considered amount of load shed is that of the DN, otherwise is that of the transmission network.

IV. The Case Study Applied to the Portuguese Electrical System

When designing a conventional UFLS scheme, load values are an estimate of the real demand. The values are estimated differently for the TSO and the DSO. The TSO estimates the demand using snapshots of the grid, of a week day in one of the peak demands during daylight period. The load percentage is then estimated dividing the load of the feeder by the maximum synchronous load of the substation. The DSO provides the load value of a feeder considering the maximum synchronous load of the DSO substation. The estimated percentage is then obtained dividing that value by the maximum synchronous load of the TSO substation.

The values used for the DG refer to maximum active power that it can inject into the grid. These are often the same as the nominal power of the generator. The data concerning these values is property of the DSO operator, thus it is organized to meet its own purposes. In order to be able to use this data, in the TSO's perspective, the DG connection point had to be related to the TSO's substation. Therefore, to identify the TSO's substation the DN single diagrams had to be used, and the results were placed in a spreadsheet.

The efficiency of the ranking algorithm was assessed by studying the following scenarios and comparing them with the actual UFLS plan (Case Base scenario):

- Scenario 1: a determined set of weights is used, and the closed loops in the DN are not considered;
- Scenario 2: the same set of weights as in scenario 1 is used, and the closed loops in the DN are considered;
- Scenario 3: a different set of weights is used, and also considers the closed loops in the DN.

A. Main results

Using this ranking algorithm allowed, in general, obtaining very satisfactory results. Nevertheless, it is needed to perform a trade-off analysis, because it is not possible to minimize the loss of DG without affecting critical consumers. Note that load values used in this paper are an estimate of the real demand, thereby should not be considered extremely accurate. Furthermore, to allow the comparison of the studied scenarios with the current load shedding plan the 48.8 Hz frequency step is merged with the 49.0 Hz in the 1st frequency step, because the former is not considered in the existing UFLS plan.

Through the obtained results was drawn the conclusion that the Base Case is tripping too many feeders with DG, affecting 26 % of the total installed capacity. As shown in Fig. 4, in the third scenario it is possible to minimize the total loss of DG to 4.9 %. Furthermore, comparing with the Base Case and considering only the first frequency step, it can be concluded that the reduction is even greater: from 10 to only 1 % loss of the total DG installed capacity. In the second scenario a significant reduction is observed in comparison with the Base Case, being the total loss of DG of 7.5 % [1].

The load-shedding plan studied in scenarios 1 and 2 allowed to reduce the tripping of priority consumption. Relatively to the Case Base, the reduction is from 18 % to only 1 %. In those scenarios, tripping of low and medium priority consumption increased to 50 %, as showed in Fig. 5. In the third scenario a slight reduction of 7 % in tripping priority load is observed, when compared with the Case Base. In what shedding priority load is concerned, it is noted that the UFLS plan analysed in the third scenario presents the worst performance while the first and second scenarios present the best results [1].

The total number of shed feeders diminished in comparison with the Base Case. It allowed a reduction of 89 feeders to 63, 67 and 70, in scenarios 1, 2 and 3, respectively. In a practical point of view, these numbers show how the effort of setting the relays at substations can be reduced.

As far as the topology of the DN is concerned, it is concluded that there are no significant improvements to justify not considering the closed loop feeders, as in the first scenario. This would imply installing relays with specified frequency settings with the purpose of undoing the loops on the DN. An incorrect functioning of the relays could jeopardize the UFLS plan. Thus, it is concluded that the UFLS plans considering closed loops, as in scenarios 1 and 2, achieve almost the same results with the advantage of being simpler.

The geographical distribution as well as the distribution per frequency step is balanced. Nevertheless, in Fig. 6 it is noticed the smaller quantity of load shed in the Central area of the country. This result is not surprising because the number of feeders that contribute to the UFLS plan, located in the country's Central area, is very small.

In the TSO's perspective, the total sum of shed load is about 35 %, whereas in the DSO's it is about 20 %, as showed in Fig. 4.

Of all studied scenarios, in comparison with Case Base, it may be concluded that the set of weights used in scenarios one and two, respectively, allowed to reduce the loss of DG and significantly avoid the tripping of priority demand. The set of weights used in the third scenario made it possible to minimize the loss of DG, at the cost of jeopardizing priority consumption [1].

In the overall assessment, it can be concluded that by using the ranking algorithm presented in this paper it is possible to improve the performance of the UFLS plan.

V. Conclusions

In this paper, Distributed Generation was included in the analysis of the load shedding plan, aiming to minimise its loss when a predetermined frequency fall occurs. The obtained results showed that by using the designed algorithm it is possible to find a systematic process for determining under-frequency relay parameters, considering the trade-off between shedding critical consumers and shedding Distributed Generation. It was also possible to determine the best under-frequency relay parameters, aiming to minimize the loss of DG and to avoid shedding critical consumers.

The study of different scenarios allowed to conclude that the goals have been met, revealing quite significant improvements in comparison to the current UFLS. Therefore, using this algorithm allows the TSO to define new frequency settings that may be applied in the relays at the substations in a short term period, improving the efficiency of UFLS control measure for emergency situations.

This algorithm is useful independently of the UFLS scheme being used. Whether it is a conventional or an adaptive scheme, allowing the choice of which feeders should be included in the UFLS plan.

The development of this algorithm brought to the TSO the following added values:

- Systematise the process for determining the under-frequency relay parameters;
- Allow a different approach for the load-shedding problem, considering DG in the Distribution Network;
- Help the system frequency to recover faster than with the current plan, as less Distributed Generation is shed;
- Prevent shedding larger amounts of consumers;
- Reduce shedding priority loads.

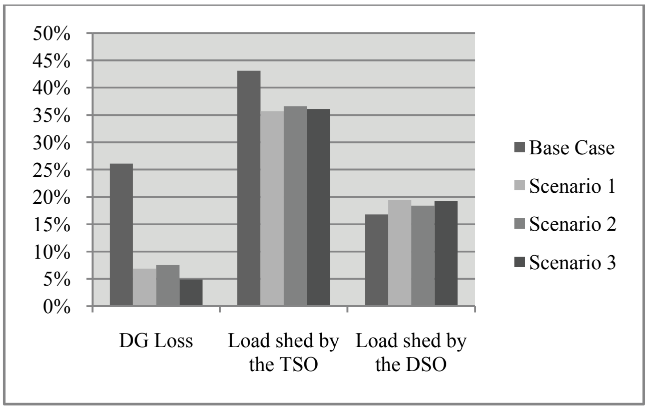

Fig. 4. Overall comparison between scenarios: percentage of DG loss and percentage of load shed per TSO and DSO.

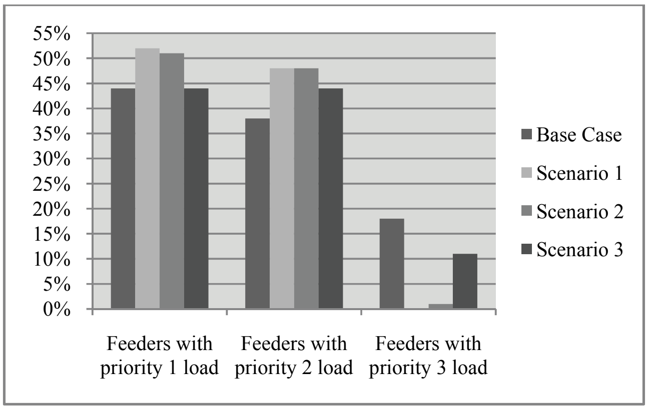

Fig. 5. Comparison of the different load priorities shed per each scenario.

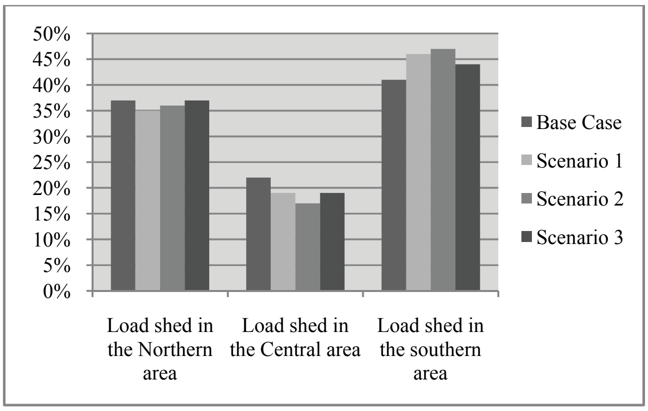

Fig. 6. Comparison of the geographical balance of the load shed percentage in each area per scenario.

VI. Future Developments

Despite conventional under-frequency load shedding schemes have reduced improvement margin due to the uncertainty associated with the data used, different approach to load estimation might result in shedding fewer loads. Simultaneity factors may also be used for each type of DG, such as wind based, solar based, combined heat and power, mini hydro, among others, seeking to use the best values to estimate the most probable active power generated at peak demand periods. It's also suggested to compile a load priority list suited to load shedding.

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VIII. Biographies

Ricardo V. Fernandes was born in Porto in 1983. He received his "Licenciatura" (a five year course) and his "Mestrado Integrado" (M.Sc.) in Electrical Engineering and Computers, both in Power Systems, from Faculdade de Engenharia da Universidade do Porto (Oporto University, Portugal), in 2006 and 2008, respectively. He carried a period of studies for one semester in the course Technology for Sustainable Development, in the Technische Universiteit Eindhoven (Netherlands), in 2005. He is with Rede Eléctrica Nacional, S. A. since 2006. Currently he is working with the Grid Operation Department in the System Operator Division.

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Fernando P. Maciel Barbosa received the "Licenciatura" degree (a five year course) in Electrical Engineering from FEUP (Porto University) in 1971 and the M.Sc. and the Ph.D. degrees in Power Systems from UMIST in 1977 and 1979, respectively. His main research interest areas include Power System Reliability and Power System Analysis. He is a full Professor of Electrical and Computer Engineering with FEUP, where he has been since 1971. He has published several research papers in national and international conferences. He is a CIGRÉ member and participates on CIGRÉ WG6, Distribution Systems and Dispersed Generation. He is member "Conselheiro" of the Portuguese professional association of Engineers "Ordem dos Engenheiros" and an IEEE Senior Member.

Rui Pestana received his "Licenciatura" and "Mestrado" degrees in Electrical Engineering and computers from Instituto Superior Técnico, Lisbon, Portugal, in 1986 and 1990, respectively. He is with Rede Eléctrica Nacional, S.A. since 1989, and he is the Head of the Studies and Development department of the System Operator Division since 1995. He is member of the Portuguese professional association of Engineers. He is a regular member of CIGRÉ C2 Study Committee. He is corresponding member of the TF NACM, TF ITC SG1, TF 14 and EIC of ETSO. He is corresponding member of the ESS of UCTE. Mr. Pestana is member of the WINDGRID, ANEMOS.plus, PEGASE and WG2 of the SmartGrid EU projects.