Identification of the Horizontal Network Interconnecting the Portuguese and Spanish Electrical Power Systems

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***Abstract*-In this paper it is proposed a technique to identify the relevant neighbouring electric power systems using the Horizontal Network methodology. The relevant network of the Spanish system was established, taking into account the actual interconnections and the new cross-border tie-line in Douro International with a voltage level of 400 kV. All simulations of the Portuguese and Spanish transmission systems were performed using the computational software package PSS®E from Siemens/PTI. The savecases used in this study represent pictures of the real systems. From the simulation results, some conclusions that provide a valuable contribution to the understanding of the impact of the new interconnection between the two countries will be pointed out.**

***Index Terms*-- Cross-borders Electricity Transits, Electric Power Systems, Horizontal Network, Security Analysis**

I. Introduction

Nowadays, due to security reasons, guarantee of supply and reliability the interconnection of the Electrical Power Systems (EPS) of different countries is mandatory. The establishment of a European Network of Transmission System Operators for Electricity, ENTSO−E, increases the cooperation and coordination among transmission system operators (TSO) in strategic areas of their activity. Among these, there is the coordination of system operation and the development of the European Network [1].

The new paradigms associated with the restructuring of the electricity sector made it critical to develop new methodologies to study and analyze the security of the power networks [2]. Furthermore, there has been a continuing effort to reinforce the interconnections between the networks in order to avoid congestion and improve safety [3]. The interconnection capability between Portugal and Spain, as well as with the rest of the ENTSO-E electric power network is of particular importance, since it allows the international trade and a mutual assistance among the systems.

The horizontal network of the neighboring systems is one of the important issues that Energy Management System (EMS) will have to take into account in order to identify the relevant external network. The transmission lines that are significantly affected by cross-border trading comprise the so-called horizontal network [4]. For most countries, the horizontal network consists of the 400 kV interconnections, transmission lines and substations at least. This concept can be equally applied to existing or future transmission lines [5].

Electrical utilities are confronted daily with unforeseen events in their power networks that may reduce the security level and consequently endanger essential service to the consumers [6], [7]. The Iberian cross-border transmission capacity might be subject to significant fluctuations in time, due to the variability of the generation level and unpredictable consumption patterns, as a result of accidental or planned outages of its components [8].

Commercial use of the interconnections requires that those participating in the energy market have information, in advance, about the available transmission capacity, to implement the import and export programs. Different scenarios of generation, consumption forecast and credible information on the prediction of system outages in each horizon are taken into account in order to evaluate the cross-border availability, avoid transmission congestion and market splitting [9]. Effective congestion management is one of the major tasks performed by the TSO and a fundamental aspect for a reliable and efficient operation of an electricity market. If the interchange capacity is limiting the market, it will split the Iberian market and will have two market prices [10].

In May 2011, the interchange capacity between the two Iberian systems was approximately 2100 MW from Spain to Portugal and 2200 MW in the opposite direction. It is expected that these capabilities will be reinforced until 2014, allowing to achieve an interchange capacity of approximately of 3000 MW which will be available in both directions. This should reduce significantly the level of congestion that affects the interconnections between the two systems. In order to accomplish this expansion strategy, it is essential to implement new corridors:

- Two lines between Lagoaça and Aldeadávila with a voltage level of 220 kV,
- One line between Lagoaça and Aldeadávila with a voltage level of 400 kV,
- One line between Tavira and P. Guzman with a voltage level of 400 kV,
- One line between Vila Fria and O. Covelo with a voltage level of 400 kV.

Currently, there are eight cross-border tie-lines in the Iberian network with voltage levels from 130 kV to 400 kV. A new tie−line between Lagoaça (Portugal) and Aldeadávila (Spain), in the Douro International area, with a voltage level of 400 kV is under construction and is expected to be completed during 2011. With this new cross-border interconnection it is essential to understand how the National Transmission Grid will be affected. It is expected that the reinforcement of electricity interconnections between the two countries improves the security and competitiveness of domestic energy supply [10].

In this paper it is proposed a technique to identify the relevant neighbouring electric power systems using the horizontal network approach. The developed methodology was applied to the Iberian systems in order identify relevant external network of Portugal. All simulations were performed using the computational software package PSS®E, developed by the Siemens/PTI.

II. Identification of the Horizontal Network

The European Parliament, aiming to establish fair rules for trade in electricity, thereby increasing the competition in the internal electricity market, taking into account the specificities of national and regional markets, created the Regulation (EC) No. 1228/2003 [11]. This regulation will require the creation of a compensation mechanism for cross-border flows and the establishment of harmonized principles with regard to charges for cross-border transport and the allocation of available interconnection capacity between national transmission systems. This compensation scheme is called the Inter-TSO Compensation (ITC) and aims to support the development of the internal electricity market [12].

The ITC must provide a mechanism to offset the costs of hosting cross-border flows, including the provision of cross-border access to the interconnected system [13]. The ENTSO-E has a background in order to compensate the operators of the transmission system to accommodate the cost of electricity flows across borders [14].

The TSO must identify the relevant network areas to international flows. Such identification results in the definition of the horizontal network, which includes all network elements, that are significantly affected by cross border flows [15]. The horizontal network corresponds to the part of the transmission system, which is used to transmit electricity across countries and inside the country. It contains the transmission system components that are influenced significantly by cross-border energy exchanges.

The horizontal network determination is based on the variation of flows on lines and transformers when adding a transit, i.e., a flow entering on a set of tie-lines and exiting through another set. Each country is studied independently. Tie-lines are modelled as the only external injections or extractions from the network of each country. It is impossible to simulate all possible transits through the network; as there are too many possible patterns and an infinite number of possible magnitudes. However, any transit through a country can be seen as a combination of several individual transits.

The horizontal network was defined using the transit flow of 100 MW between every combination of interconnection lines. Import flow of 100 MW on one interconnection line and export flow of 100 MW on the other interconnection line made a combination. During simulation procedure of one transit – 100 MW import and export on two of interconnection lines – flows of others interconnection lines were set up to zero.

For the determination of the horizontal network it is used the DC model for load flow simulation on an empty network:

- An empty network is a real network reduced to a list of nodes, with the description of all the grid elements connecting them, with no consumptions, no generations and no flows on the tie-lines, before the introduction of one-to-one transits.
- The DC power flow approximation is a simplification of the complete AC model, which allows a simplification of the network equations by neglecting the reactive part of flows and by assuming that magnitudes of nodal voltages are equal. In all the usual operational situations, this approximation gives very similar results to a complete AC model.

The DC power flow modelling process starts from the well known AC transmission line shown in Fig. 1 [16] and the only variables are voltage angles and active power injections.

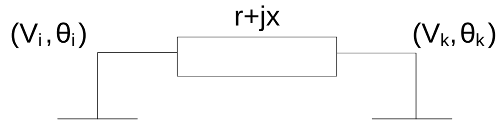


Fig. 1. Series transmission line model.

The DC approximation is based on the main two simplifying assumptions [17]:

- The phase shift between the two end buses of a line is small, so a first order development can be used to express:

$$\cos(\theta_i - \theta_k) \approx 1 \tag{1}$$

$$\sin(\theta_i - \theta_k) \approx \theta_i - \theta_k \tag{2}$$

- The voltage magnitude of a bus is close to its nominal value, with these assumptions, the active power flow can be obtained by:

$$F_{ik} = \frac{1}{x_{ik}}\left(\theta_i - \theta_k\right) \tag{3}$$

The use of a DC power flow model is limited to those MW oriented applications where the effects of network voltage and VAr conditions are minimal. As opposed to using the AC power flow model, the perceived advantages of a DC model are as follows [17]:

- A computation using a DC modelling is much faster than one using an AC modelling as it allows a direct calculation of the solution rather than an iterative one.
- The DC model always finds a solution while an AC method may not converge.

– It is required less network data and only use well known information, such as active load and reactance, while for the AC approach it is necessary to know the reactive load or reactive power generation that are much more difficult to obtain.
– Active losses are not taken into account in a DC approach.
– The DC model linearity fits the economic theory on which much of transmission-oriented market design is based.

In order to find the horizontal network the transmission lines that belonging to a given nation must be clearly identified. This is accomplished by applying a standard 100 MW flow between each couple of nodes connecting the selected country with the others, all the national lines carrying a power greater than or equal to 1 MW are considered belonging to the horizontal network of the selected country, since it was the threshold value of the horizontal network for the ITC rate.

Formally the procedure is the following one [16]:

Criterion

$$\text{If } \underset{l,m}{Max}\left(\left|F_e(t_{lm})\right|\right) \geq 1 \text{ MW} \quad \text{then } e \text{ is part of the horizontal network} \tag{4}$$

Notations

e - grid element (circuit or transformer)

t_{lm} - the 100 MW individual transit normalized between tie-line l and tie-line m

$F_e(t_{lm})$ - flow in the grid element e due to the t_{lm} individual transit

In Fig. 2 it is shown an example of the technique applied to identify the horizontal network between two countries. The main goal is to find the transmission lines of country "B", that are significant for the cross-border transit of country "A" with three interconnection nodes. When there are $n\times(n-1)$ transits for each individual part only $n\times(n-1)/2$ simulations are considered, since there are overlapping flows in the network (n – is the number of tie lines of the country with its neighboring countries). In this example just three simulations were required to find the elements that belong to the horizontal network.

All transmission lines, which are usually operated, are connected in order to represent the transmission system in normal operation conditions. In the first simulation, a generator unit of 100 MW is placed in the sending end of a cross-border tie-line and a load of 100 MW is located in the receiving end of other interconnection tie-line between the two countries. It is run a power flow using the DC model and the lines influenced by the elementary transit are identified, i.e., the flows between any pair of nodes at the borders of the area.

For each grid element, the simulations give a list of flows for all the possible individual transits. Only the absolute value of transits is retained. According to the criterion specified in (4), an element is inserted in this list when the maximum value is equal or greater than 1 MW. If the maximum value is lower than 1 MW the element is not a part of the horizontal network, i.e., components with transit flows that are lower than the threshold value are not taken into account, since the line is not influenced by the elementary transit.

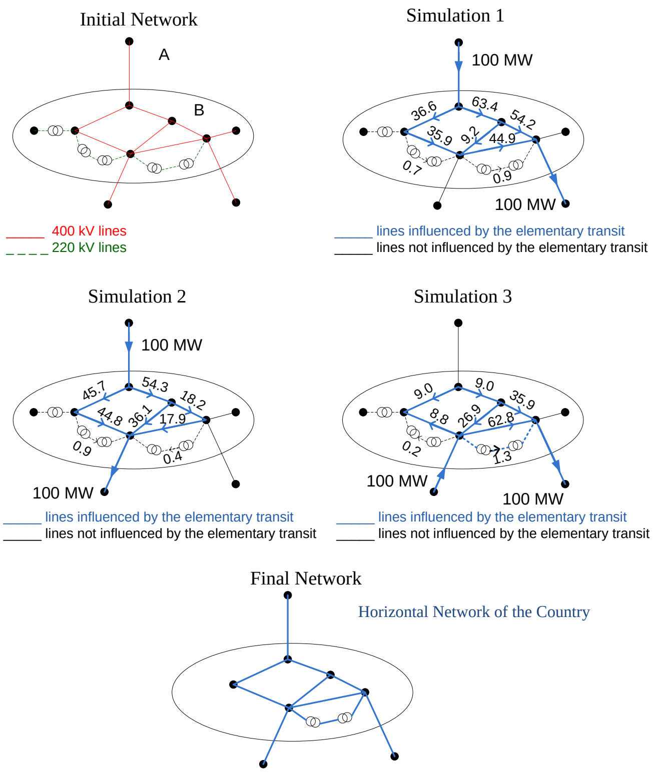


Fig. 2. Horizontal network example.

In simulations 2 and 3, is performed the same procedure. In each simulation, the transmission lines belonging to the horizontal network are identified with the colour blue, since they have a transit of energy greater than 1 MW. Bringing together all the simulations, thus determines the relevant external network of country "A", represented as a "Final Network", in Fig. 2. It contains the transmission system elements that are influenced significantly by cross-border exchanges. The methodology of the horizontal network, in general, only applies to voltage levels equal to or greater than 220 kV.

III. Application Example

The proposed methodology was applied to the Iberian systems in order to identify the transmission lines of the Spanish grid that are relevant for the Portuguese power network. The Iberian systems comprise 1161 buses, 221 generators, 336 loads, 76 fixed shunts and 959 lines and transformers. The network analyzed has eight interconnections between Portugal and Spain that include already the new interconnection between Lagoaça and Aldeadávila, in Douro International area, with a voltage level of 400 kV. These interconnections are shown in Table I.

In order to identify the relevant external network of Portugal, the generators, the fixed shunts and loads have been removed from the Portuguese network, as well as buses and transmission lines, except those that have links with Spain.

TABLE I
INTERCONNECTIONS BETWEEN PORTUGAL AND SPAIN - VOLTAGE LEVES

Portugal	Spain	Voltage
Alto Lindoso (*SAL*)	*Cartelle* 1 (*ECTL*1)	400 kV
Alto Lindoso (*SAL*)	*Cartelle* 2 (*ECTL*2)	400 kV
***Lagoaça* (*SLGC*)**	***Aldeadávila* (*CAAE*)**	**400 kV**
Falagueira (*SFR*)	*Cedillo*(*CCIE*)	400 kV
Alqueva (*SAV*)	*Brovales* (*EBVL*)	400 kV
Pocinho (*SPN*)	*Aldeadávila* 1 (*CAAE*1)	220 kV
Pocinho (*SPN*)	*Aldeadávila* 2 (*CAAE*2)	220 kV
Pocinho (*SPN*)	*Saucelle* (*CSLE*)	220 kV

Fig. 3 presents the interconnections between the two Iberian networks.

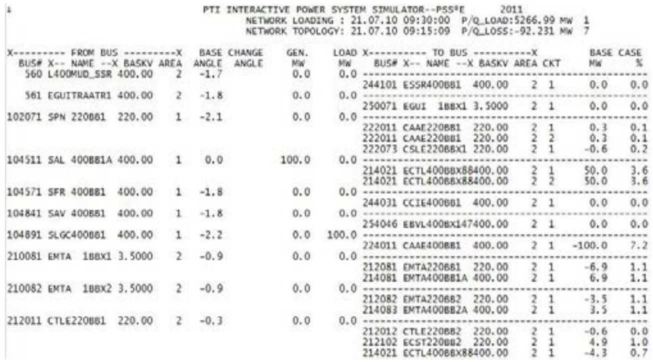
Fig. 3. Cross-border tie-lines between Portugal and Spain.

IV. RESULTS

In the study of the Iberian network eight interconnections were taken into account, including the new tie-line between Portugal and Spain. In this case, there are $8 \times (8-1) = 56$ transits, although only 28 simulations were performed due to overlapping flows in the network.

For each interconnection is used a 100 MW generator and a load placed on other interconnection. The power flow study was performed using the *DC Network Solution and Report* module of the PSS®E program. The results were analyzed and it was assumed that an element belongs to the horizontal network when the elementary transit was greater than or equal to 5 MW, otherwise it was removed, since the EMS requires this threshold value in order identify the relevant external network [18]. This procedure was repeated until all possible cases were analyzed.

The cross-border tie-lines SAL-ECTL1 and SAL-ECTL2 have no power flow associated, since it is the same interconnection. The same happens in the interconnection SPN-CAAE1 and SPN-CAAE2. In the first simulation a generator of 100 MW was connected to SAL bus and a load of 100 MW connected to bus SLGC [18]. In Fig. 4 it is shown the results obtained for this simulation.



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1                              PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS®E      2011
                                    NETWORK LOADING : 21.07.10 09:30:00  P/Q_LOAD:5266.99 MW  1
                                    NETWORK TOPOLOGY: 21.07.10 09:15:09  P/Q_LOSS:-92.231 MW  7

X--------- FROM BUS ---------X  BASE CHANGE    GEN.    LOAD X---------- TO BUS ----------X        BASE CASE
 BUS# X-- NAME --X BASKV AREA  ANGLE  ANGLE    MW      MW    BUS# X-- NAME --X BASKV AREA CKT      MW     %
  560 L400MUD_SSR 400.00   2    -1.7            0.0     0.0 ------------------------------------------------
                                                             244101 ESSR400BB1   400.00   2  1       0.0    0.0
  561 EGUITRAATR1 400.00   2    -1.8            0.0     0.0 ------------------------------------------------
                                                             250071 EGUI  1BBX1 3.5000   2  1       0.0    0.0
102071 SPN 220BB1  220.00   1    -2.1            0.0     0.0 ------------------------------------------------
                                                             222011 CAAE220BB1   220.00   2  1       0.3    0.1
                                                             222011 CAAE220BB1   220.00   2  2       0.3    0.1
                                                             222073 CSLE220BBX1  220.00   2  1      -0.6    0.2
104511 SAL 400BB1A 400.00   1     0.0          100.0     0.0 ------------------------------------------------
                                                             214021 ECTL400BBX88400.00    2  1      50.0    3.6
                                                             214021 ECTL400BBX88400.00    2  2      50.0    3.6
104571 SFR 400BB1  400.00   1    -1.8            0.0     0.0 ------------------------------------------------
                                                             244031 CCIE400BB1   400.00   2  1       0.0    0.0
104841 SAV 400BB1  400.00   1    -1.8            0.0     0.0 ------------------------------------------------
                                                             254046 EBVL400BX147400.00    2  1       0.0    0.0
104891 SLGC400BB1  400.00   1    -2.2            0.0   100.0 ------------------------------------------------
                                                             224011 CAAE400BB1   400.00   2  1    -100.0    7.2
210081 EMTA  1BBX1 3.5000   2    -0.9            0.0     0.0 ------------------------------------------------
                                                             212081 EMTA220BB1   220.00   2  1      -6.9    1.1
                                                             214081 EMTA400BB1A  400.00   2  1       6.9    1.1
210082 EMTA  1BBX2 3.5000   2    -0.9            0.0     0.0 ------------------------------------------------
                                                             212082 EMTA220BB2   220.00   2  1      -3.5    1.1
                                                             214083 EMTA400BB2A  400.00   2  1       3.5    1.1
212011 CTLE220BB1  220.00   2    -0.3            0.0     0.0 ------------------------------------------------
                                                             212012 CTLE220BB2   220.00   2  1      -0.6    0.0
                                                             212102 ECST220BB2   220.00   2  1       4.9    1.0
                                                             214021 ECTL400BBX88400.00    2  1      -4.3    0.7
```

Fig. 4. DC Network Solution and Report produced by the PSS®E.

In Fig. 5 to 8 it is shown some of the elements belonging to the relevant network in various interconnections of the Iberian network, since they present a power flow greater than or equal to 5 MW. The transmission lines with a voltage level of 220 kV are marked in green whereas the 400 kV lines are marked in red.

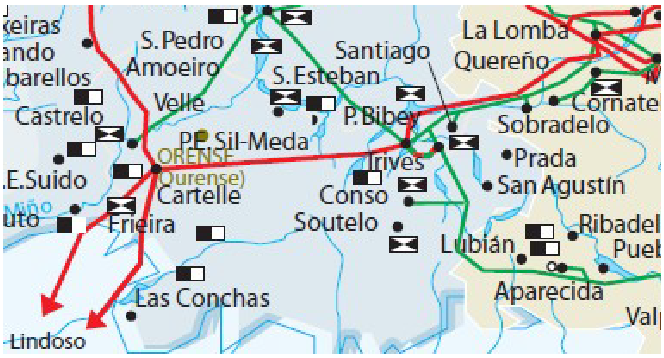

Fig 5. Relevant network in the area of Alto Lindoso.

Fig 6. Relevant network in the areas of Lagoaça and Pocinho.

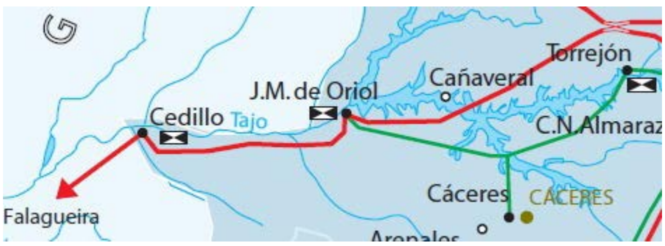

Fig 7. Relevant network in the area of Falagueira.

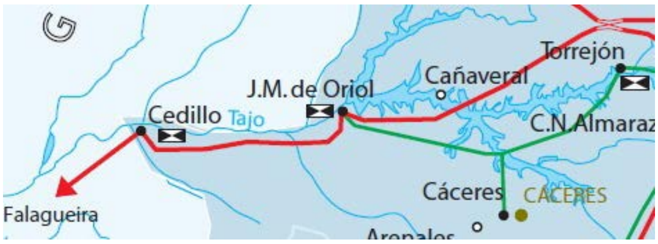

Fig 8. Relevant network in the area of Alqueva.

In Table II it is presented the transit equal or greater than 50 MW for the new 400 kV tie-line between Lagoaça and Aldeadávila in the Douro International area.

TABLE II
TRANSMISSION LINES NEARBY THE SLGC–CAAE INTERCONNECTION WITH A TRANSIT EQUAL OR GREATER THAN 50 MW

Bus *i*		**Bus *j***		**Flow [MW]**
Name	**Voltage [kV]**	**Name**	**Voltage [kV]**	
SLGC	400	CAAE	400	100.0
SFR	400	CCIE	400	100.0
SAV	400	EBVL	400	100.0
CAAE	400	CVLE	400	56.7
CCIE	400	SFR	400	100.0
CCIE	400	EJMO	400	100.0
EBVN	400	CAZE	400	54.0
EBVN	400	EBVL	400	87.2
SLGC	400	CAAE	400	100.0

The relevant network is obtained based in all simulations and contains the elements that have been marked, i.e., those with an elementary transit greater than the threshold value. In Fig. 5 it is presented the relevant external network of Portugal obtained by combining the results of the 28 simulations [18].

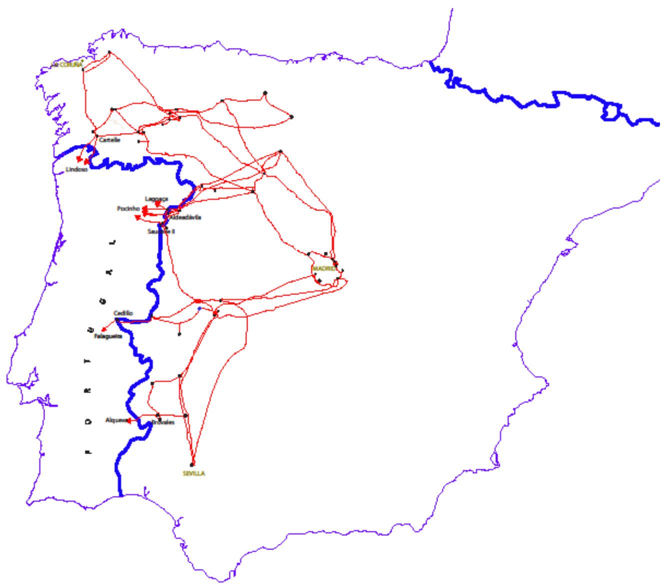

Fig 9. Relevant external network of Portugal.

In Table III it is presented the elements of the horizontal network, which is composed of buses belonging to the Spanish power system. It was considered that only the voltage levels equal or greater than 220 kV were relevant to establish the horizontal network [18].

TABLE III
ELEMENTS OF THE HORIZONTAL NETWORK

Bus	**Voltage [kV]**	**Bus**	**Voltage [kV]**
CAAE	220	EBVL	400
CAAE	400	EBVN	400
CAZE	400	ECAC	220
CCIE	400	ECHA	220
CORE	220	ECMP	400
CSLE	220	ECON	220
CVLE	220	ECST	220
CVLE	400	ECTL	400
EALM	220	EEAL	220
EALV	220	EFUE	400
EAPR	220	EGAL	400
EBAL	220	EGUI	220
EBAL	400	EGUI	400
EHER	400	ESSR	400
EJMO	400	ETOJ	220
ELLB	220	ETOR	220
ELLB	400	ETOR	400
ELOE	400	ETRI	220
ELRB	400	EVDC	400
EMER	220	EVLE	400
EMOR	400	EVLP	220
EMRL	400	EVPR	220
EMTA	220	EVVC	400
EMTA	400	EZAM	220
EMTS	400	SANE	400
EMUD	400	SGTE	400
EPBI	220	SHJE	400
EPGR	400	SMVE	400
ERIC	220	STVE	400

The relevant external network of Portugal is composed by 59 elements of the Spanish grid. Most of the network identified is located in northwest of Spain, with special relevance to the region of Galicia. In the north, as it is shown in Fig. 10, the horizontal network extends to Puentes de García Rodríguez, near A Coruña.

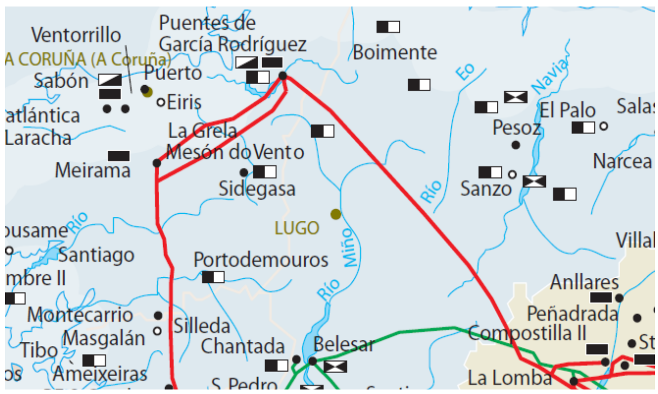

Fig 10. Location of the further north substations.

In the east, as it is presented in Fig. 11, the relevant network extends to Madrid and includes the following nodes: Galapagar, Morata, Moraleja Loeches, Villaviciosa and San Sebastian de los Reyes. As it is shown in Fig. 12, to the south, the network reaches Guillena

Fig 11. Location of the further east substations.

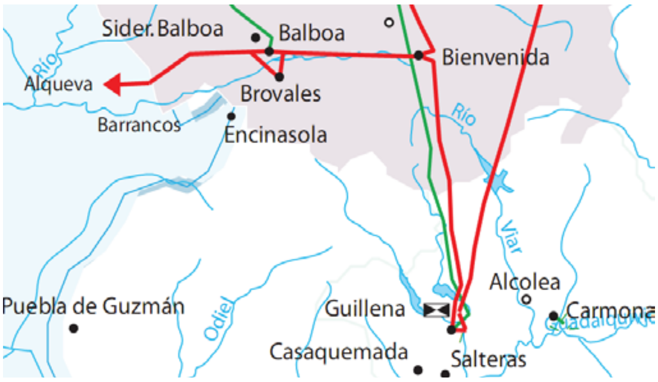

Fig 12. Location of the further south substations.

V. Conclusions

In this paper it was presented a methodology to identify the relevant electric power network of a neighbouring country or area, using the horizontal network scheme. The main purpose of this study was to identify the relevant Spanish electric power network due to the new cross-border interconnection between Portugal and Spain, in the Douro International area, since it is essential to understand how the National Transmission Grid will be affected. It is expected that this new tie-line will improve the security and the competitiveness of domestic energy supply. It was proved that the proposed technique is feasible when applied in a real world problem. The horizontal network is the part of a transmission system, which is used to transfer electricity between countries. It contains the transmission system elements that are influenced significantly by cross-border exchanges. The use of the horizontal network method is relatively simple, easy to understand and implement, speeds up considerably the evaluation of the relevant neighbouring systems for each scenario and enables an acceptable simulation time. The relevant network is obtained considering all simulations with an elementary transit greater than the threshold value established by the system operator. Most of relevant external network of Portugal is composed of lines located in the northwest area of Spain and as it was expected located mainly near the border.

Acknowledgements

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