Planning to Expand?

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Digital Object Identifier 10.1109/MPE.2007.904764

Looking at Mainland Spain to See the Importance of Well-Planned Transmission Expansion

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THE APPROPRIATE FUNCTIONING OF THE TRANSMISSION NETWORK OF AN electric energy system is critical for an electricity market to thrive. Moreover, since the annual cost (investment and operation) of a transmission network is a small percentage of the cost of the energy (and ancillary services) traded throughout the year in the market, and since a transmission problem might have dramatic effects on trade disruption, a well-managed and properly planned transmission network is a key requirement in a well-designed electricity market.

We describe our view of the fundamental ingredients of transmission expansion planning within the framework of an electricity market including competitive generating companies and competitive load-serving entities as well as independent producers and consumers. We assume the transmission network to be a centrally managed entity pursuing maximum social welfare.

We understand expansion planning to include:

- ✔ building new substations, cables, and lines
- ✔ repowering existing lines, including both the upgrading to increase the transmission capacity maintaining the voltage level and the substitution of old lines for other ones of higher voltage
- ✔ installing transformers and reactive power compensators (reactances and capacitor banks).

While undertaking expansion planning responsibilities within a competitive market, a key issue to emphasize is the need of coordination with:

- ✔ load-serving entities and large consumers (e.g., railway networks) to locate where the demand grows
- ✔ generating companies (including wind power and cogeneration producers) to identify new generation sites
- ✔ distribution companies operating distribution networks, which are fed from the transmission network
- ✔ public policy entities in charge of land management and urban development
- ✔ environmental protection authorities.

We illustrate the transmission expansion planning methodology using the transmission network of mainland Spain, managed by Red Eléctrica de España (REE), the transmission system operator (TSO) of the electricity market of mainland Spain (EMMS). It should be noted that REE is also the system operator of this market (http://www.ree.es).

The Electricity Market of Mainland Spain

For background purposes, the basic information of the EMMS is provided below. The data refers to 2005 (http://www.ree.es).

Total installed capacity is 73.970 GW. The generation mix includes hydro (22.5%), coal (15.4%), nuclear (10.6%), oil (9.0%), combined-cycle gas turbines (16.5%), and renewable sources and co-generation (25.9%). Note the high percentage of renewable and co-generation capacity.

Annual peak power demand is 43.378 GW. Annual energy demand is 246.187 TWh. The supply of this energy demand includes

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coal (29.4%), nuclear (21.9%), combined-cycle gas turbines (18.5%), hydro (7.3%), oil (3.8%), and renewable sources and co-generation (19.1%). Note the high percentage of energy produced by renewable and co-generation sources. The highest daily energy demand is 837 GWh. Available transmission facilities include 16,846 km of 400-kV lines and 16,458 km of 220-kV lines.

The electrical interconnection of the Iberian peninsula (Spain and Portugal) with France is below 3.5% of the peak demand in Spain. That is, the Iberian peninsula is almost an island from an electrical point of view. It is relevant to note that within Spain no relevant transmission problem exists.

The EMMS was launched in January of 1998. It includes a day-ahead market, a reserve market, and a set of balancing and adjustment markets. These markets are cleared based on auctions within a daily framework. A market operator clears most of these markets (http://www.omel.es). Markets involving both economical and technical issues are cleared by the system operator. Bilateral contracting is possible but not commonly used due to financial barriers. A forward and futures market was created in July 2006 (http://www.omip.pt). It encompasses both Spain and Portugal, i.e., the Iberian Electricity Market.

Since the launch of EMMS, most of the trade has taken place through the day-ahead market. REE as system operator ensures technical feasibility pertaining to both generation and transmission. The market is foresighted by a market regulator with primarily advising capabilities (http://www.cne.es). Enforcement power remains with the Ministry of Industry (http://www.mityc.es).

The trading sector has not flourished as regulated tariffs have been clearly below the market prices. As cheap regulated tariffs are available, most consumers (particularly industrial ones) choose to be subjected to tariffs, not market prices.

Market prices are complemented with significant capacity payments based on the availability of power plants, payments which are intended to promote generation investment.

The recent introduction of a CO_2 emission market has originated a significant increment in the electricity prices, as production companies have raised their respective offer prices to account for emission costs (http://ec.europa.eu).

A Centralized TSO Paradigm

As a result of considering the transmission network a natural monopoly, we assume that the TSO is a single regulated entity serving the considered electric energy system, which operates and plans the transmission network pursuing social welfare. In the case of the EMMS this entity is REE. This is the common situation in most Western European countries and Canada.

However, note that multiple profit-oriented TSOs can operate within an electricity market provided that appropriate regulation is enforced. This is the most common situation in the United States. In the analysis below, we do not consider this alternative perspective.

From a Centralized Operation to a Competitive One

In a centrally managed electric energy system, the system operator controls generally the generating units, the transmission and distribution networks and the demands, and should expand the transmission network is such a manner that both generation and transmission costs are minimized subject to meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.

In a competitive market, the TSO, in charge just of the transmission network, should expand this network minimizing transmission cost (investment and operation) and pursuing maximum social welfare while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.

How to resolve the tradeoff minimum transmission investment cost versus maximum social welfare is not a simple task and results in different objective functions for different TSOs. Different criteria include:

- ✔ maximizing trading possibilities (pool and contracting) to the benefit of competing generating companies and competing load serving entities, as well as other consumers and producers
- ✔ maximizing social welfare as defined by the market operator while clearing the market
- ✔ maximizing network reliability
- ✔ minimizing environmental impact
- ✔ others.

The final criterion considered by a given TSO takes into account multiple objectives, generally conflicting with each other. Nevertheless, in order to achieve the guarantee of supply established by the Spanish Electric Power Act (Law 54/1997, available in English at http://www.cne.es/), REE pursues maximum reliability within budget constraints and other general considerations described below.

Expansion Planning Criteria: Horizon and Methodology

The fundamental criteria pertaining to transmission expansion planning within a competitive environment include for all plausible operating conditions (including the extreme ones):

It should be emphasized that the transmission expansion planning problem is essentially multiyear (dynamic) as investment decisions span and are carried out throughout several years.

- ✔ minimizing investment and operations network cost
- ✔ achieving a secure and efficient static and dynamic functioning of the network
- ✔ complying with appropriate environmental, administrative, and social requirements.

It should be emphasized that the transmission expansion planning problem is essentially multiyear (dynamic) as investment decisions span and are carried out throughout several years. However, a common simplification is to consider a single target year.

The transmission planning analysis in REE spans a 10-year horizon and focuses on the final year and on an intermediate year. For instance, the planning horizon 2002-2011 focuses on the year 2011 and on 2008. Results below refer to the year 2011.

The expansion planning methodology in REE consists of the following four fundamental steps:

Step 1: Multiple scenario generation covering the whole planning horizon and detailed analysis of these scenarios.

Step 2: Information structuring and index calculation.

Step 3: Identification of competitive and necessary network reinforcements.

Step 4: Decision making.

These steps are detailed below.

Step 1. Scenario Analysis

About 400 scenarios are generated to identify all plausible operating conditions defined as combinations of load conditions, generation profile, and network status. Particular care is exercised to identify the extreme scenarios. Each scenario has associated a probability of occurrence. It should be noted that this set of scenarios properly describes the operating conditions pertaining to the 8,760 hours of the target year (2011 for the results reported below).

The scenarios must comply with the following requirements:

- ✔ to cover the expected range of demands for the duration of the considered target year: peak and extreme peak loads, extreme off-peak load, as well as other relevant load conditions
- ✔ to characterize all the technical constraint violations in the system (overloads and high and low voltage bounds)
- ✔ to exhibit the expected variability of fuel prices, hydro conditions (wet and dry), wind conditions (high and low), international exchanges, etc., throughout the considered target year.

Scenarios are characterized for both the static and the dynamic viewpoints. For the static analysis an optimal power flow (OPF) tool is used, while for the dynamic analysis a transient stability tool is used. From the dynamic perspective, exhaustive transient stability analyses are carried out. From the static point of view, the *N*-1 criterion is used for generating units, lines and transformers; and the *N*-2 criterion for double circuit lines, substations with a high level of generation or transformation, and substations with very short fault clearance times.

Generating cost pertaining to OPF simulations are obtained for each available technology by properly forecasting fuel costs.

Step 2. Information Structuring

Once scenario information pertaining to a whole year is gathered, diverse criteria and indices are used to summarize the information embedded in the scenarios.

Two criteria are introduced below that help with the assessment of scenarios and reinforcement alternatives:

- ✔ Criticality: Impact that the failure of a given element has on the other elements, in terms of overloads and noncompliance with voltage limits.
- ✔ Sensitivity: Impact on a given element (overloads in lines or transformers and voltage deviations at nodes) as a result of the failure of the other elements of the system.

Three types of indices are used to characterize scenarios:

- ✔ Extreme values (maxima and minima). These values enable the detection of the largest overloads, overvoltages and undervoltages, regardless of the probability of the contingencies that cause them and of the probability of the scenarios that originate them.
- ✔ Probability-weighted RMS values. These indices are calculated as the root mean square value of relevant magnitude (overloads, overvoltages, and undervoltages) values expressed in per unit and weighted with the corresponding probabilities.
- ✔ Probability-weighted deviations over limits. These indices are calculated using the products of the deviations (observed values minus limit values) and the probabilities of the corresponding scenarios.

The combined use of the three types of indexes above gives the planner an overall view that would not otherwise be obtained, and which enables the decision-maker to make decisions knowing that the calculated values already include a double perspective of impact-probability and sensitivity-probability.

Step 3. Identification of Network Reinforcements

Based on the planner experience, the identification of the relevant reinforcements is achieved by taking into account the degree of criticality and sensitivity of each transmission corridor. The objective is to achieve a network that works without limit violations for all (or most) scenario realizations.

Then, a cost-benefit analysis is carried out to identify the most competitive reinforcements from the relevant ones. Within the cost-benefit analysis, investment and operating costs must be properly balanced so that the whole operating lives of the diverse reinforcement elements are considered.

Investment network costs include the actual investment in new equipment and its operating and maintenance cost, as well as its replacement cost. Operating network costs include basically the costs associated with active power losses and the reliability costs.

Step 4. Decision Making

Once scenario information and indices are available, appropriate charts and graphs are produced to facilitate the decision-making process to the managers in charge of such decisions. Using this information, the decision maker defines the most appropriate expansion plan.

It is relevant to note that, on average, building a new line requires six years; a new substation four years; a transformer, reactance, or capacitor bank three years; and the repowering of an existing line two years.

The following section illustrates some of the information available for the decision maker.

2005–2011 Planning Results

Considering the transmission network of mainland Spain, the methodology presented above has been used to analyze year 2011 within the planning period 2002–2011. Results below refer to a revision of this analysis that was carried out in 2004, spanning the period 2005–2011, by REE.

Figure 1 presents the average values of the demands throughout Spain for the duration of the year 2011. The areas with the greatest demand can be clearly identified: central Spain (Madrid), northeast (Barcelona), and east (Valencia).

Figure 2 depicts the average values of the generation throughout Spain for the year 2011. The northwest and

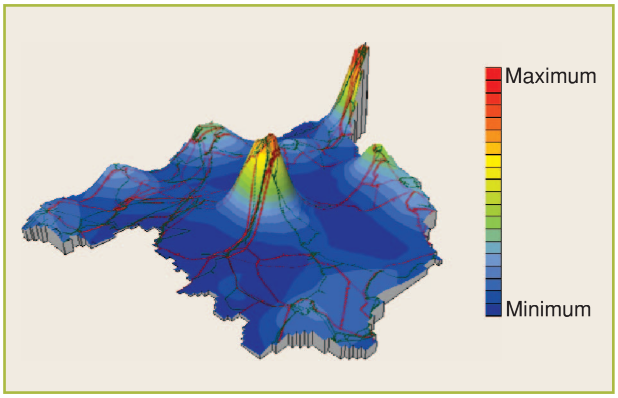

figure 1. Average value of demand throughout Spain during the year 2011 (MW).

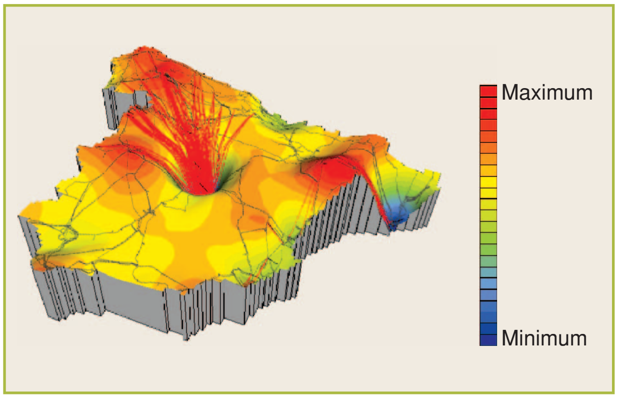

figure 3. Average power flow generation-demand throughout Spain during the year 2011 (MW).

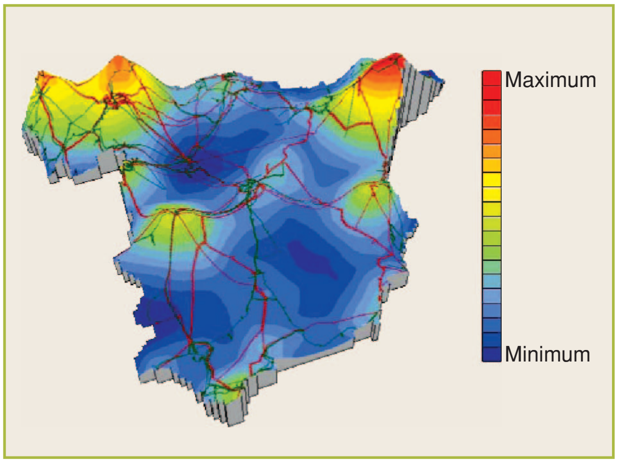

figure 2. Average power generated throughout Spain during the year 2011 (MW).

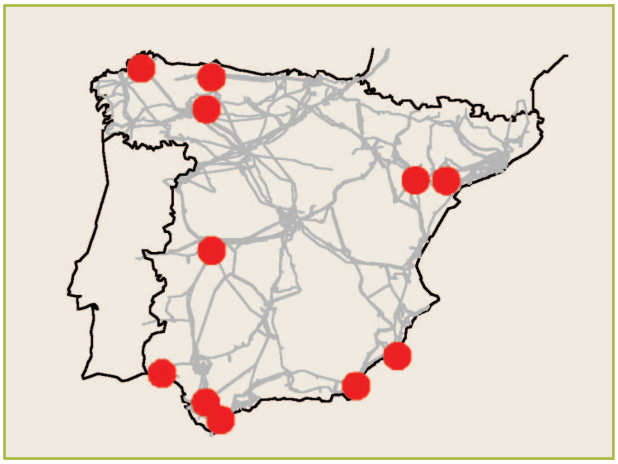

figure 4. Areas with the highest energy production during the year 2011.

northeast areas concentrate the greatest energy productions. In contrast, central Spain (Madrid), which is the area with the highest demand, has a very low generation capacity.

Figure 3 illustrates the differences between the generation and the demand throughout Spain. In this way, the direction and magnitude of the average power flows during the year 2011 are represented. Observe that the central and northeast areas attract most of the power flows.

Figure 4 presents the areas of the system where the highest concentrations of production occur. These areas are particularly prone to problems of transient stability (dynamic behavior of the system). Potentially problematic areas include northwest, northeast, central-west, and the south.

The average values of the voltages at 400-kV buses during the year 2011 are shown in Figure 5, while Figure 6 illustrates voltage standard deviations. Voltage magnitudes are sufficiently high throughout the peninsula but in the northeast area. Voltage standard deviations are comparatively high also in the northeast area.

The short-circuit current values at the 220-kV buses, for a winter peak scenario of 2011, are shown in Figure 7. Three areas with high short-circuit current values are easily identified: central Spain (Madrid) and northeast (Barcelona), which are meshed zones, and the Duero River along the border with Portugal, which is a zone with a high concentration of production.

Finally, the expansion plan of the transmission network for the planning horizon 2005-2011 is detailed in Figures 8–11. Figure 8 shows the new lines and substations planned. Figure 9 shows the new 400/220-kV transformer units to be built. Figure 10 shows the new reactive power compensation elements (reactances in green and capacitor banks in brown). Figure 11 depicts the repowering to increase the capacity of some existing lines.

Summary

Within an electricity market that embodies a single TSO that manages and plan the transmission network pursuing economic efficiency and maximum social welfare, we described the fundamental ingredients of transmission expansion planning. The single TSO approach is the most common situation in Western Europe. The transmission planning methodology involves four major steps: comprehensive scenario generation and analysis, information

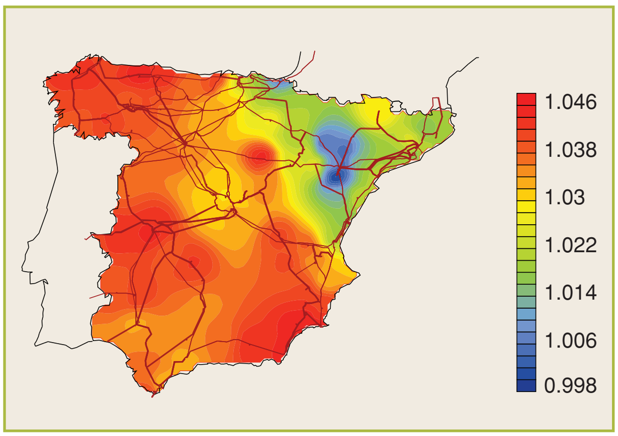

figure 5. Average voltage values (per unit) at 400-kV buses during the year 2011.

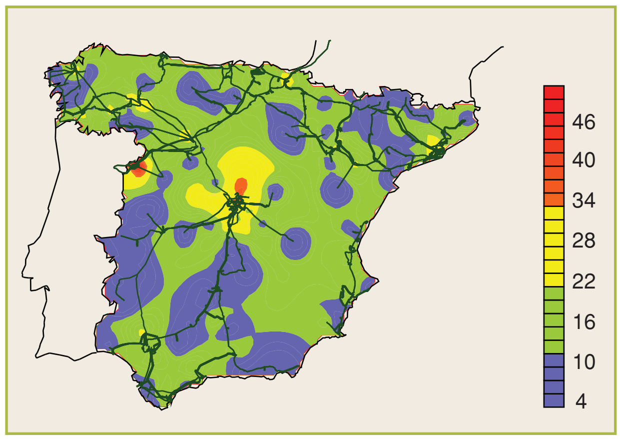

figure 7. Short-circuit currents (kA) at 220-kV buses for a winter peak scenario of the year 2011.

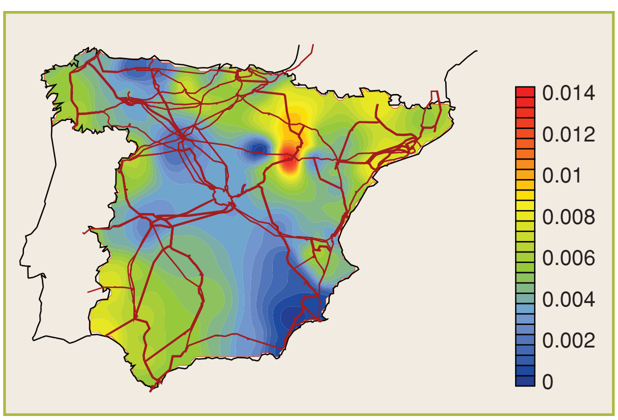

figure 6. Voltage standard deviations (per unit) at 400-kV buses during the year 2011.

figure 8. Expansion plan for 2005–2011: new 400-kV lines and substations.

figure 9. Expansion plan for 2005–2011: new 400/220-kV transformers.

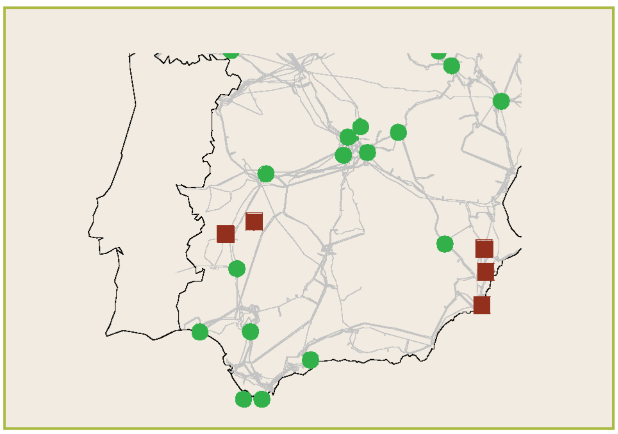

figure 10. Expansion plan for 2005–2011: new reactances (circles) and capacitor banks (squares).

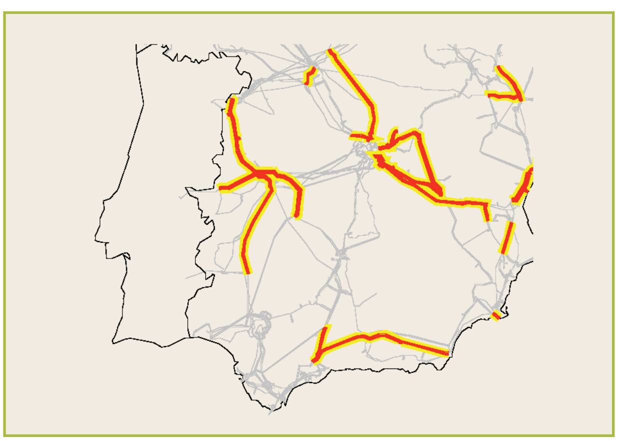

figure 11. Expansion plan for 2005–2011: repowering of existing 400-kV lines.

structuring, identification of competitive expansion alternatives, and decision making. These steps are illustrated through the case of the electricity market of mainland Spain and its TSO, Red Eléctrica de España.

Acknowledgments

We thank Juanma Rodríguez from REE for his help in arranging the team that wrote this article.

For Further Reading

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Biographies

Rafael de Dios received the electrical engineer degree in 1985 from Universidad Politécnica de Madrid, Spain. Since 1998, he has been working at Red Eléctrica de España in the areas of transmission planning, generation planning, system operation, electricity markets design, ancillary services, and electric power systems economics and regulation of the Spanish power system.

Fernando Soto received the electrical engineer degree in 1981 from Universidad Politécnica de Madrid, Spain. He joined Red Eléctrica de España in 1985, where currently he is head of the Network Planning Department. Additionally, he is chairman of the Spanish National Committee of CIGRE.

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IN "PLANNING TO EXPAND?" BY RAFAEL DE DIOS, FERNANDO SOTO, and Antonio J. Conejo (in the September/October issue of *IEEE Power & Energy Magazine*, pp. 64-70), portions of Figures 9, 10, and 11 were cut off in the production process. The figures appear in their entirety below.

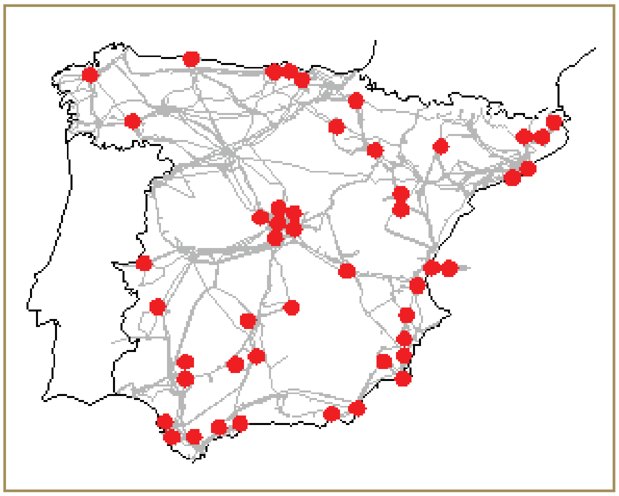

figure 9. Expansion plan for 2005–2011: new 400/220-kV transformers.

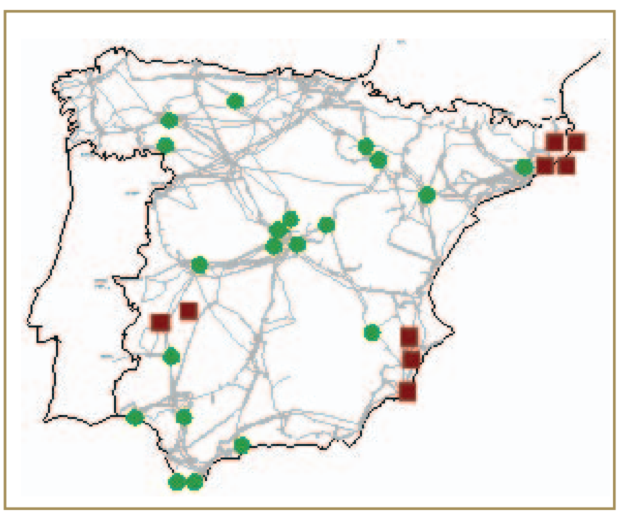

figure 10. Expansion plan for 2005–2011: new reactances (circles) and capacitor banks (squares).

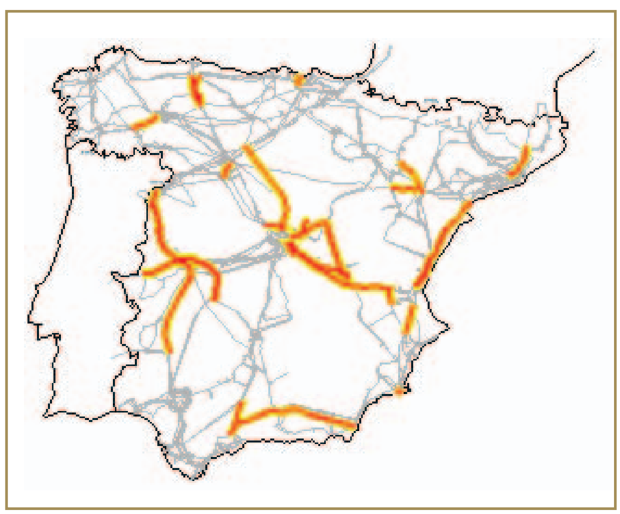

figure 11. Expansion plan for 2005–2011: repowering of existing 400-kV lines.

Digital Object Identifier 10.1109/MPE.2007.909153