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# UNDERGROUNDING AND REORGANIZATION OF THE ELECTRICAL SYSTEM OF THE CITY OF MADRID

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## *ABSTRACT*

*Nowadays, the strong growth and fast development of cities require the reorganization and modernization of their electrical systems, with a view to be able to satisfy the present and increasing demands, and the future ones of the new industrial and residential areas.*

*The execution of this project, committed to the environment and of doubtless social benefits, requires the collaboration, support and will of the different official administrations such as City and County Councils, etc.*

*This one of a kind project not only comprises the undergrounding of more than 120 km of overhead lines that range from MV to EHV, but also the dismantling of old lines, substations compaction and the reduction of the visual and environmental, economic and social impact that the electrical infrastructures produce on high density urban nuclei.*

*This paper identifies the key points for the achievement of the project, starting with the network planning and the creation of standardized components, the optimized design, participation of the public administrations and utilities, including suppliers pre-qualification and finally the coordination of the different contractors.*

## *KEYWORDS*

Underground, XLPE, cable system, High Voltage, EMF, horizontal drilling, gallery, installation, environment.

## 1. BACKGROUND

Nowadays, there is considerable public pressure against overhead lines that can be summarized by the well-known NIMBY effect (Not In My Back-Yard), which describes the phenomenon in which residents oppose a development as inappropriate for their local area, but do not oppose such development in another's.

In Spain, there is an intense debate on the possible health risk from electromagnetic fields, not only from the powerlines but also from mobile phone antennas.

Moreover, concerns regarding aversion to powerline towers and property devaluations have played a powerful part when considering the construction of overhead powerlines and have forced the undergrounding and reorganization of the electrical system of the city.

Cable systems based on current technology, and compared to overhead powerlines, have several advantages from social and environmental standpoint:

- Socially accepted
- Negligible visual effect
- Small right-of-way
- Low overall electromagnetic fields
- Lesser land depreciation
- No noise or corona activities
- Small transmission losses
- Less prone to failures

## 2. PROJECT FEATURES

Iberdrola is implementing a major project of reconstruction of the powerlines of the city of Madrid, also known as Plan Madrid within the company.

This project is comprised of the following major parts:

- Construction of 16 Compact Substations (GIS)
- Dismantling of more than 125km of overhead lines
- Construction of more than 180km 220kV, 132kV 66kV and 45kV underground lines

## 3. PLANNING

As previously said, the project comprises both Medium Voltage (MV) and High Voltage (HV) networks. However, in HV extra consideration had to be taken into account due to the following aspects:

- Some are part of the backbone of the transmission system. Thus, reliability is the highest priority.
- The higher the voltage level, the more difficult it is to design and coordinate cables and accessories.
- HV cable systems are subjected to higher electrical stresses, thicker insulation and greater thermo mechanical effects.

The cable route selection is done taking care of minimizing the impact on the environment and social community, always considering the most cost-effective alternative. For each powerline project it is assessed the impact of the construction on this topics: Land use, geotechnical and soil condition, traffic and parking affection, archaeology, health and safety, electromagnetic fields and the social-economical benefits.

The routes are selected in consultation with public agents, private landowners, considering affected infrastructures and services to get the most favourable routing.

Although the networks are located in an urban environment, the terrain features different conditions such as heavily trafficked roads, railway, motorway and water crossings and special interest zones.

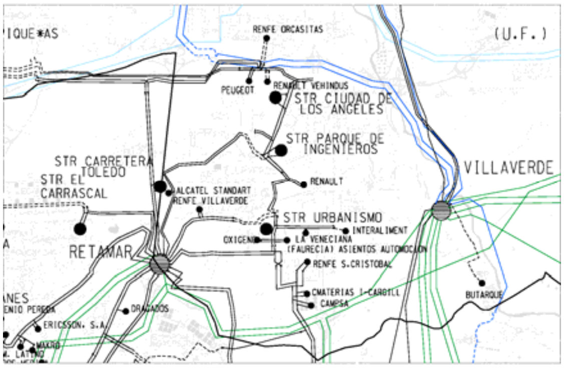


**Figure 1:Excerpt of the old network**

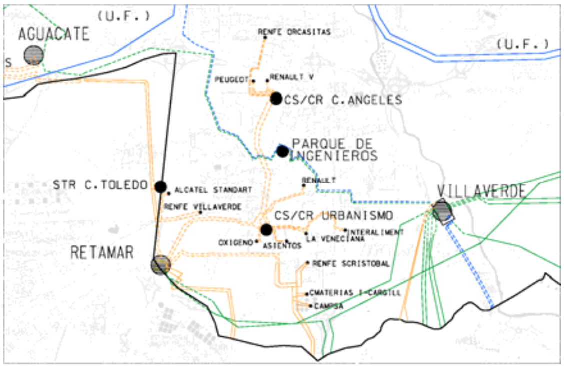


**Figure 2:Excerpt of the new network**

## 4. DESIGN

### 4.1 Cable System

#### 4.1.1 Cable

It was decided to focus on XLPE and HEPR insulation technology, not considering other technologies such as OF, PPLP, and so on that require more maintenance.

The type of cable used has been standardized relating to the voltage level as follows:

| | 220kV | 132kV |
|---|---|---|
| **Conductor** | 2000 mm$^2$ Cu | 1200 mm$^2$ Al |
| **Screen** | 206, 280, 315, 350 Cu Wires | 102, 172, 280, 350 Cu Wires |
| **Insulation** | XLPE | HEPR XLPE |
| **Rating** | 560 MVA | 210 MW |

Cables are calculated for a rating of 100%, in standard environmental conditions and in trefoil arrangement, which the typical values for underground powerlines in urban areas.

Simple cable construction has been chosen in agreement with manufacturers, so most companies can comply with it.

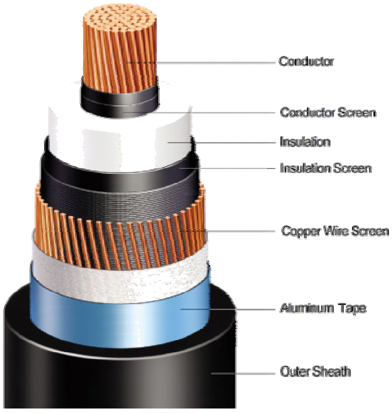


**Figure 3:Cable cross-section**

#### 4.1.2 Accessories

For the whole project, SF6 and outdoor terminations are needed. For the outdoor terminations, it is mandatory to use composite insulation, rather than porcelain, for security of personnel and equipment in case of explosions.

The manufacturers are given flexibility regarding the technology to use on the terminations. Although there is some preference for dry type, silicon oil is also used on some terminations even though there is more maintenance operations linked to this technology.

The manufacturer is responsible for the whole cable system, ensuring, at least, a 5-year warranty period on parts and labour.

Other accessories, such as surge arresters and other substation equipment, are supplied by the utility to the cable contractor, which has to install it. This way, a major reduction in costs is achievable.

#### 4.1.3 Earthing

Another important characteristic in the rating of the underground powerlines is the earthing method, apart from the thermal limitations.

Taking into account the length of the involved power lines and with views to suppress the circulation currents in the metallic screens that reduce the ampacity, the earthing methods used were crossbonding and single point bonding. In some cases, in order to have the minor sections of each the of major sections equal, a special bonding system was applied, that is to say, mixing both earthing systems.

### 4.2 Electromagnetic fields

A consequence of the technological development is the increase of electromagnetic fields, to which we are exposed daily. Although the state-of-the-art in this matter is clear and the World Health Organization states that "*All reviews conducted so far have indicated that exposures below the limits recommended in the ICNIRP (1998) EMF guidelines, covering the full frequency range from 0 - 300 GHz, do not produce any known adverse health effect*", in some occasions controversies arise, so it is prudent to adopt the ALARA (As Low As Reasonably Achievable) criteria in this matter.

Frequently underground powerlines are presented as a solution to reduce EMF exposure. This is true for electric fields; but is not that clear for the magnetic field. Comparing to an overhead powerline the magnetic field profile decreases more rapidly with the distance. However, it is higher in the surrounding area of the powerline's axis. This matter is shown in the following picture, were both profiles are shown for standard installations and a 1000A conductor ampacity.

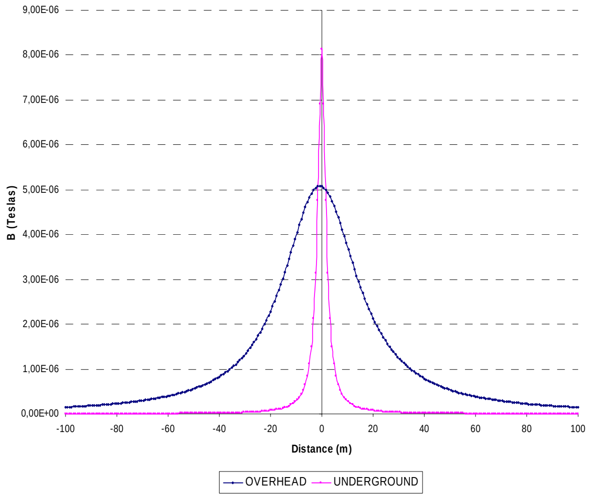


**Figure 4: Overhead and underground Magnetic field comparison**

Based on the result from in-house research studies, the following actions have been taken to meet previous statements:

- o Increase the distance from the cable route to public exposure
- o Reduce the spacing between each phase
- o Trefoil arrangement of the phases
- o Phase order re-arrangement in multi-circuit installations

These studies presented trefoil configuration as the best arrangement for the reduction of the EMF, comparing to the flat lay configuration. Then, the best phase arrangement has been calculated in order to reduce even more the magnetic field value.

The following drawing depicts the optimal phase arrangement in multi-circuit lines in order to minimize EMF.

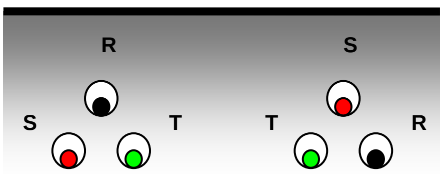


**Figure 5: Optimal phase arrangement in trefoil formation**

Next graphic, shows the magnetic field profile at 1m above the ground for the trefoil configuration, for the maximum phase current of 1427 A, in both arrangements: standard (RST RST) and optimal for EMF minimization (RST STR).

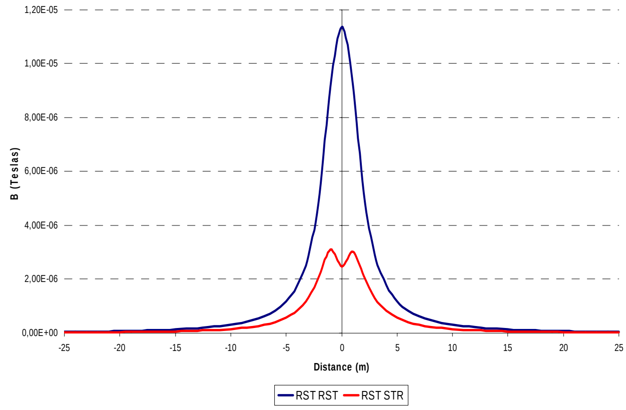


**Figure 6: Magnetic field profile**

With the selected cable arrangement, magnetic field above the ground does not exceed 4 µT, which is much less than the regulated maximum of 100 µT.

## 5. CONSTRUCTION

The cables are laid in a trefoil configuration, as it is a compromise between low EMF emissions and power rating.

The nominal burial depth is 1,5 m, however, it varies depending on the crossings and terrain conditions. Along with the power cables the optical fibre is also installed in the same trench, but at a different height for maintenance purposes. These fibres are used for communications between the substations and the control centre, and the spare ones for broadband communications.

This trench solution of a duct bank embedded in concrete is not only for mechanical protection against external aggressions, but also to separate civil works from cable laying. This flexibility enables civil works to be carried out during favourable periods of time (weekends, vacations, etc.) without interfering with the public.

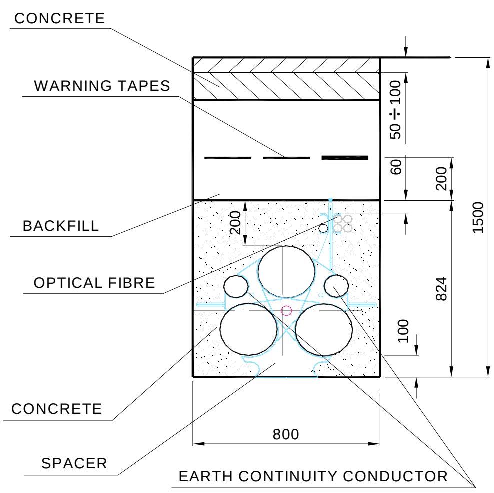


**Figure 7: Trench**

A special duct spacer was designed to ease the construction process. The aim of this spacer is to prevent duct bank flotation during concrete pouring, controlling ducts positioning along the route and ensure proper concrete cover of the duct bank.

**Figure 8:Duct spacer**

Regarding joint bays, traditional processes involved building them in situ. It was decided to design a new type with prefabricated components to ease the installation, minimizing construction time. Completion time is reduced from several weeks to several days.

**Figure 9: old joint bay**

**Figure 10: new joint bay**

The height had to be sufficient for the splicing work to be done under safe and comfortable conditions due to the fact that the shelter of the joint bay is part of it. This feature enables the start of the covering process once the elements are placed, thus reducing inconvenience to the public. The length of joint bays were designed to fit two joints. This way, in case of failure of the cable or joint, two joints could be made without the need for civil works or other operations.

It was also developed a new joining system between the joint bay and the surface by means of a tubular system to ease the process of cable laying.

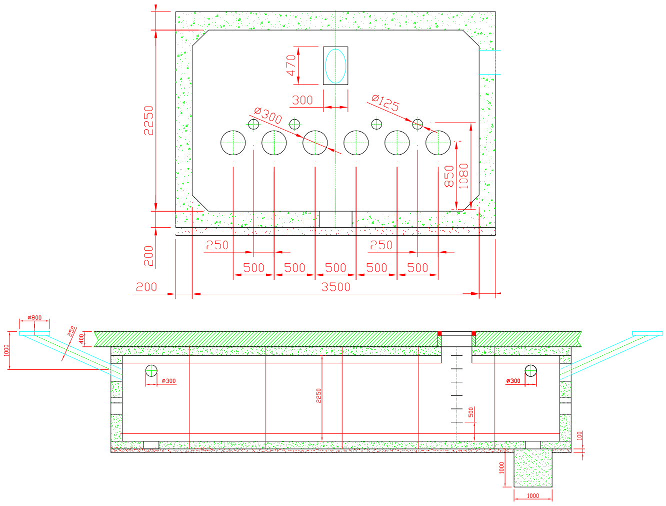


**Figure 11: Joint bay profile view**

This new type of joint bay is in line with the idea of splitting civil works and cable installation, introduced with the duct bank trench. Therefore, enables more flexibility in the construction schedule, minimizes the impact on traffic and inconveniences to the residents.

The joint bay is left empty, not filled with sand or other backfill, in order to enable periodic maintenance. A rigid clamping system is applied to the cables at each joint bay, so that no thermal expansion loops are needed in the bay. Hence, joint chamber dimensions are independent of cable length, and the dimensions can be reduced as there is no need to fit the expansion loops.

In some cases, powerlines are installed in shared services galleries. Cables would be vertically and horizontally stacked on metallic structures. There are several advantages compared to standard trenches:

- Ease of cable installation, repair and maintenance
- Economic and faster installation
- Improved protection against external aggressions

**Figure 12: Cables in shared services galleries**

There are crossings that require flat arrangements near the surface, as this is the only way to execute it. In this case, an steel metal plate is installed on top of the cables in order to provide mechanical protection, distribute pressure over the cables and to minimize the electromagnetic field.

Horizontal directional drilling makes it possible to install powerlines under obstacles, such as rivers or roads, without disturbing the surface. That is the case with several crossings in the Manzanares river, M-40 highway and railways.

**Figure 13: Directional drilling**

The dismantling of the overhead powerlines is not executed until it is no longer necessary for the area supply. It could whether by re-routing the supply to that area, and hence overloading other powerlines, or after the commissioning of the corresponding underground powerline.

**Figure 14: Overhead line dismantling**

## 6. PROJECT MANAGEMENT

The following teams are assembled, in charge for the different parts of the project:

**Engineering:** This team develops the engineering project: Preliminary routes, topographical surveys and project design. In addition, was in charge of design of the trench, new joint bay and the spacer. Also, drafts the material, processes and equipment specifications that afterwards will be needed in the tendering and construction phases.

**Permitting:** The activities this group is involved are project endorsement by the professional association, conversation with public authorities, community relations, route permits, planning license, crossing licenses, and all the involved rates and fees. In order to involve the public, the authorities and other service providers, periodical consultation meetings are held in each area where the powerline was going to be installed. In Spain, it is mandatory to have State and Local permits before starting any construction work

**Procurement:** Starting from the conversations with companies and finishing with the contract adjudication are responsible for all contracting strategies, that is to say, the whole service and materials purchasing process.

**Management:** Supporting and monitoring the rest of the groups, is in charge of the project, setting the overall strategy and schedule. In addition, manages all the construction items, materials and process in order to comply with the project correct execution and deadlines. Also, is responsible for the coordination between all suppliers and contractors, on a day-to-day basis. Moreover, the financial and economical management is also a task for the management team.

**Environmental, Quality and Health and Safety Control:** There are three Security and Health Managers with several technical assistants that complements their work, all supervised by the own utility prevention service. Their work is to prevent, monitor and mitigate safety concerns that may arise during the project. Also, there is another team in charge of quality and environmental issues.

### 6.1 Management

For the completion of this construction project, a different approach is taken depending on the different working areas: MV and HV.

On the one hand, MV powerlines are executed with internal resources of Madrid's region in a decentralized way using the company's global resources. The first step, the engineering of each project, is already done by means of standardized construction type projects, where all the details and alternatives are specified. The project manager has to develop the scope of construction works, define the materials to use based on the type project and hire the contractors. This way, it is relieved from unnecessary responsibilities and tasks, with the support of the company resources, just having to follow the construction details.

On the other hand, HV projects, which are more critical and require more responsibility, are done with a different method. A full working team is set up, which act as a general contractor with all the responsibilities: Design engineering, material and equipment procurement, developing work scopes and hiring contractors. Therefore, the project manager has full knowledge of each activity, enabling the steering and allocation of resources to fulfil the master plan.

Management on both methodologies has similar focus; tasks such as planning, permitting, design, procurement, construction and reception are executed multitasked and in parallel, rather than having a linear workflow, where each phase precedes the previous one and so on. This has resulted in a faster completion time of each individual objective and the final goal.

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## 6.2 Procurement

In the procurement process, the aims are:

- Inviting adequate manufacturers and contractors to provide top class products.
- Limiting the manufacturing risk, avoiding awarding a single company the total amount of the supply or service.
- Qualifying enough manufacturers and contractors to encourage competitiveness in the tender process.
- Limiting the number of qualified companies in order to avoid unnecessary effort in the tender process.

The manufacturers are requested to submit complete quotation on each supply item and service, also detailing the manufacturing, delivery and installation schedules, based on company standards. Not meeting the deadlines supposes facing economic and other penalties.

The tendering process is all web based, where the different companies send their offers and can follow the bidding process until the final adjudication. Once the offers are accepted, they are examined on two aspects: technical and economical. In order to avoid any interference on both assessments, two independent teams that have no relation until their final report do the appraisal. This evaluation process is based upon the following items:

- Technical solution, compliant with tender's technical specification.
- Manufacturing, delivery and installation schedules, capacity and resources
- Previous experience on similar projects.
- Quality and Environmental Management Systems
- Warranty
- Price

## 6.3 Quality assurance

With a view to assure product quality and in order to gain information on the long-term reliability of cable systems, it is necessary to carry out several tests in the qualification, manufacturing and installation of these systems:

- Pre-Qualification test
- Type test
- Routine test
- Sample test
- Acceptance test
- Installation on-site test

Concerted quality programs are established with selected providers in order to assure a fast and productive procedure for material reception and delivery.

Installation on-site tests are awarded to third party laboratories, to obtain independent test results and to reduce overall project costs.

## 6.4 Environmental, Quality and Health and Safety Control

The attainment of the best preventive levels is considered to be the strategic goal and being committed to it, is assumed by the staff for all project's works.

A sanctioning procedure has been developed in the matter of health and safety that it intends to establish the infractions and to set the penalties to the different contractors during the execution of the works, as well as to award companies that put an emphasis on health and security prevention. For its application, the procedure of contractor's continuous evaluation has been created on the basis of periodical and random inspections.

Contractors' assessment is comprised of two clearly differentiated parts; firstly, a documentary evaluation and secondly on-site valuation relative to work conditions, equipment, etc.

This procedure provides a averaged ranking system of contractors in the matter of health and safety, that provides feedback throughout the rest of the project phases using a bonus/malus awarding system, such as management and procurement.

In addition, Quality Audits are made with the purpose of verifying by means of examination and evaluation of objective evidence that is applicable in the Quality and Environmental Management System.

This way, it is ensured that the project complies with ISO 9001/2000, ISO 14001/2004 and OHSAS 18001/1999 certifications.

# 7. CONCLUSION

The result of the completion of this project will be a flexible and strong transmission and distribution network, but at the same time with a reduced visual, physical and environmental impact on the city.

This project-working model is a proven solution for managing complex, large-scale projects involving multiple working-teams, suppliers and contractors.