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# THE ST. JOHNS WOOD - ELSTREE EXPERIENCE – TESTING A 20KM LONG 400KV XLPE-INSULATED CABLE SYSTEM AFTER INSTALLATION

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## ABSTRACT

*This paper deals with the 400kV cable connection between St. Johns Wood and Elstree, one of the largest XLPE cable projects in the world. This cable route is a connecting link to the city of London and was commissioned in 2005.*

## KEYWORDS

Power cables, testing after installation, partial discharges

## INTRODUCTION

The 400 kV cable connection between St. Johns Wood and Elstree in London is one of the world's largest cable projects ever: 20 km XLPE three-phase cable system including 60 cross-bonding joints and 6 GIS terminations. The system with 2500 mm$^2$ copper conductor has a transmission capacity of 1600 MVA. The cable system was laid in a tunnel ~30 m below surface.

The motivation for this outstanding project goes back to 1997, when the national transmission operator of the networks in England and Wales, National Grid (NG), decided on an upgrade of London's electricity infrastructure. The key considerations were a large number of the existing 275 kV systems in London were approaching their predicted and agreed lifetime limits, the need to maintain the reliability and security of supply, and meet growing energy demand in the capital.

## THE TUNNEL

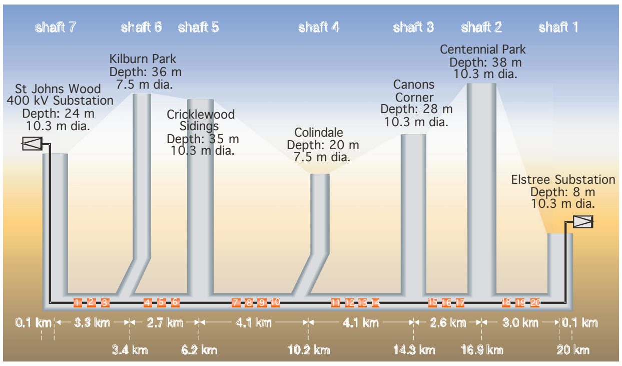

**Fig. 1 The St. John´s Wood - Elstree cable tunnel**

The cable system was installed in a 20-km-long tunnel running at an average depth of 30 m (see Fig. 1), which links the north-western outskirts of London (Elstree) with central London (St. Johns Wood).

## THE CABLE

The cable type is: 2XS(FL)2Y 1x2500 RMS/400 230/400 kV. Its outer diameter is 150 mm, and it weighs 40 kg/m. The copper conductor has a cross section of 2500 mm$^2$ with 6 segments in order to reduce skin effect losses and the XLPE insulation thickness was chosen to be 28 mm. This leads to an electrical stress of 10.8 kV/mm at the inner semi-conductive layer and 5.8 kV/mm at the outer semi-conductive layer during normal operation voltage of 230 kV ($U_N/\sqrt{3}$).

The inner and outer semi-conducting layers are bonded to the insulation material. The production process is a triple head extrusion process followed by a dry curing process to avoid water penetration into the insulation material. The metallic screen consists of copper wires which are imbedded with crepe paper to reduce mechanical and thermal impact from the screen wires on the underlying insulation. A copper screen with a 400 mm$^2$ cross section was used to meet the short circuit current requirements. The gaps between the screen wires are filled with swelling powder to achieve longitudinal water tightness.

The outer protection of the cable is provided by a laminated sheath made of extruded PE over and bonded to an aluminium foil on its inside. The PE-oversheath delivers both, high mechanical and corrosion protection of the cable. The aluminium foil provides an effective water barrier between the insulation and the outside into the cable.

For subsequent temperature monitoring of the cable route, a thin steel tube with a fibre-optic cable has been integrated into the cable shield, thus establishing representative temperature monitoring over the cable's entire length.

## THE ACCESSORIES

For this project a well proven pre-fabricated composite joint design (three piece design) was chosen and adapted to the conductor and cable size requirements [9,12].

The GIS $SF_6$-sealing ends use the well proven technology of capacitive field control by a paper wrapped cone. The dimension of the GIS terminations was chosen according to IEC TS 60859 showing a standardised interface. Both types of accessories, GIS and joint have an integrated capacitive PD-sensor.

## THE CABLE SYSTEM

For this project an extra high voltage cable system was developed and qualified with respect to the large conductor and the installation requirements. The cable system consists of 60 cross-bonding joints and 6 $SF_6$-sealing ends. The quantity of cables supplied totals 60 km. The tunnel has been designed to enable a second 400 kV system with the same transmission rating to be installed at a later juncture. For this project, a total of five additional access and supply shafts were incorporated for these options between the two end points (see Fig. 1). In addition, further 132 kV cable systems are at present being installed, laid in a triangular configuration, under the 400 kV cable system. This link between Elstree and Hendon is approximately 10 km in length.

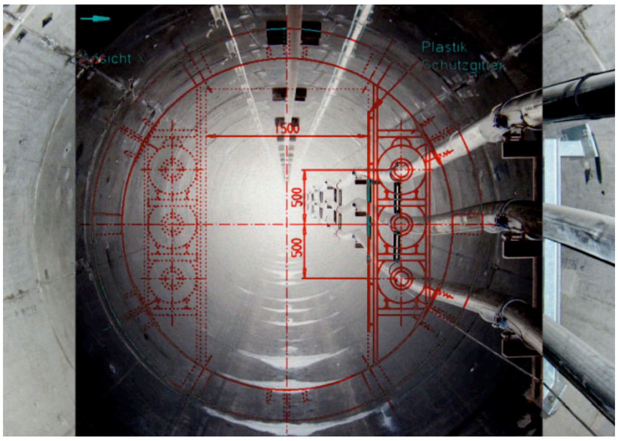

Fig. 2 The tunnel profile with the installed cable

The 400 kV system consists of three single-conductor XLPE cables arranged one above the other (see Fig. 2). The spacing between the cable centres is 500 mm in a 3 m diameter tunnel.

The cable screen is cross-bonded approximately every 957 m at each joint bay. This cross-bonding concept is designed to reduce the amount of induced sheath currents. The schematic overview of this concept is given in figure 3.

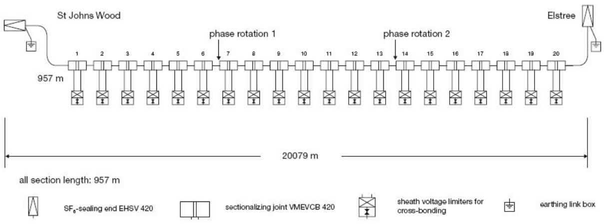

Fig. 3 System and earthing concept (diagrammatic)

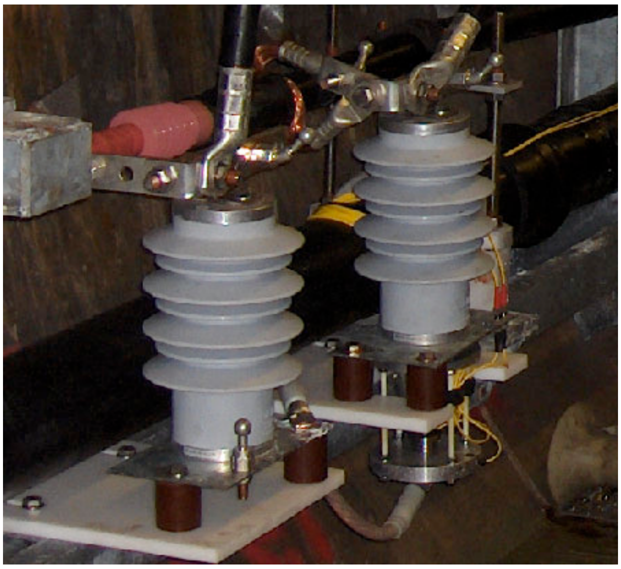

Fig. 4 Realized surge arrester configuration

Due to the fact that no system earth is provided in the tunnel a special variant of cross bonding, known as continuous cross-bonding, was chosen. The tunnel wall is regarded as non-earthed, but for installation and maintenance work earth rods are provided at each of the twenty cross-bonding points. These earthing points can be used for earthing the environment when work is being carried out in the tunnel.

The vertical laying arrangement of the cables causes significant induced voltages even under normal operating conditions. The asymmetric voltage distribution leads to equalising currents, which during operation reduce the transmission performance. Load capability calculations showed that this influence could not be neglected. To ensure that the system is perfectly balanced, a total of three equally long sections were accordingly defined in the route. By systematically changing the positions of the cables in each of these sections, the induced voltage in the cable screen is equalised to zero in the system as a whole. Phase rotation takes place between joint bays 6 and 7, and between 13 and 14 (see Fig. 3). This measure enabled the transmission performance to be increased by 5%.

In order to limit over-voltages across the cross-bonding insulating barrier in the joint, a surge arrester system (insulated against the tunnel wall) was developed (see Fig. 4). The surge arresters are connected in a triangular configuration with reference to the three-phase shield system. The sizing of the surge arresters was examined and verified by an over-voltage study conducted in the run-up to the project, simulating all operationally relevant over-voltage scenarios (e.g. short-circuits; quasi-stationary; transients; switching over-voltages and lightning impulse withstand voltages). The system was designed and tested in broad conformity with Annex D of IEC 62067 and NG standards, to withstand pulse loadings 125 kV across the disconnect or 62.5 kV between the shield and earth.

## PD SENSORS AND PD MEASUREMENT SYSTEM

All accessories (60 joints and 6 $SF_6$ sealing ends) were fitted with capacitive PD sensors (see Fig. 5) [2]. The special feature of the joints is that specifically for this project two PD sensors on both sides of the joints were provided for each joint. Here both field control elements, integrated into the silicone stress cone, were used as PD sensors.

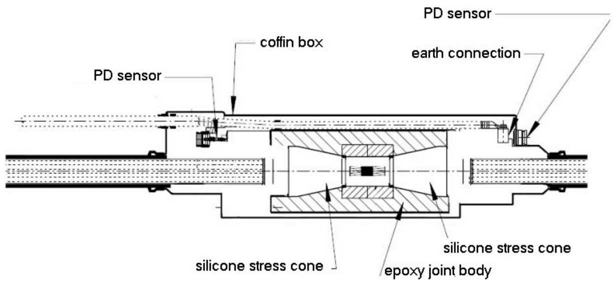

**Fig. 5: PD sensors in the joint**

It was required to enable partial discharges measurements simultaneously on all 22 accessories. Based on long-term experience with multi-channel PD measurements, a new PD measurement system was developed to make real-time 25-channel PD measurements possible. Remote control and data transmission between control computer and the distributed PD measurement channels is based on optical fibre communication. The multi-channel PD measurement system was subjected to extensive tests before practical application. The overall synchronism between the 25 PD channels was determined to approx. +/-20 ns which ensured precisely time-of-travel measurements for PD pulses. With the aid of calibration pulses, the synchronicity of the overall system was determined and confirmed to an accuracy of ±20 ns. The characteristics of the PD measuring system used are detailed in [5]. The advantages of simultaneous PD measurements at all cable accessories are elucidated in [6, 7, 8, 9, 10].

## PLANNING PHASE

**Project data:**

| | |
|---|---|
| Kick off | 1997 |
| Planning & tender | 1998-2000 |
| Contract | 2001 |
| Design and manufacturing of cables and accessories | 2002-2003 |
| Type registration | 2002-2004 |
| Installation of steelwork in tunnel | July 2004 |
| Site access hand over of tunnel and shafts | Oct. 2004 |
| Cable installation | Nov. 2004 -<br>Feb. 2004 |
| Installation of joints and sealing ends | Nov. 2004-<br>April 2005 |
| On-site tests | July 2005 |
| Clear site<br>2005 | August |

After the order had been placed in 2001, the system components were manufactured, pre-tested and delivered in 2002 and 2003. Erection work began end 2004, and ended in mid-2005. Commissioning was successfully completed with the AC voltage test in July 2005. The type registration of the cable system and all components was performed between 2002 and 2004. Highlights of the type registration procedure were an electrical type test and the long-term test of all components of the system. This prequalification test was conducted in conformity with IEC 62067 and NG standards. The long-term test consists of a one-year AC over-voltage test carried out at 1.7 $U_0$ (i.e. 400 kV conductor to earth here) on a cable loop at least 100 m long and including all accessories. In addition, 180 heating cycles with a maximum conductor temperature of 90°C (tolerance +5°/-0°C) must be successfully completed. The 400 kV prequalification test is completed with a 1425 kV lightning impulse withstand voltage test on a cable section cut from the cable test loop. A visual inspection is also carried out. All these tests were successfully completed.

## TESTING EQUIPMENT

At the very beginning of the project there was no suitable mobile AC voltage testing system available featuring the requisite performance capabilities. Though AC resonance testing of extruded HV/EHV cable systems was already common practice, no solution existed for such long cables at this time. The required test voltage was 280 kV applied to each 4.4 μF single-phase cable. This finally resulted in a test system with four reactors and exciter transformers, each fed by a frequency converter. Due to the fixed inductances of the reactors a resonant frequency of 31 Hz was obtained. The test current was 240 A at 280 kV and the test power was approximately 67 MVA [1].

Fig. 6 Mobile AC test system (280kV test voltage)

The technical solution finally adopted was to supplement existing mobile test equipment, thus enabling an AC voltage test to be conducted at 280 kV even for a cable length of 20 km. Two existing resonance reactors, each rated at 254 kV / 80 A / 16 H, were accordingly supplemented by an identically constructed third reactor, so that all three could be operated together in a parallel circuit. In order to achieve the requisite test AC voltage of 280 kV, a fourth reactor (30 kV / 240 A) was provided in a series connection. The picture for this test circuit located and erected in the Elstree substation is shown in Fig. 6.

The performance of the AC voltage testing system was tested in advance in January 2004 on a capacitor battery (comprising approximately 750 power capacitors) with an appropriate capacitance and monitored by an IR-camera (see. Fig. 7) at the IPH Berlin high-performance test bay. The test proceeded successfully, so that no changes in the basic concept were needed.

Fig.7 Test of the AC test system (280kV test voltage /1h)

## COMMISSIONING TEST

Since the cable route terminated at both ends in $SF_6$ substation entry sealing ends, the AC voltage test could only be conducted using a 400 kV outdoor $SF_6$ test bushing.

During testing simultaneous PD measurements were required to be carried out on all cable accessories of a single phase, i.e. concurrently at the two GIS $SF_6$ sealing ends and 20 cross-bonding joints over a distance totalling 20 km. At the time of contract award there was only limited experience of carrying out such simultaneous PD measurements on circuits with far fewer accessories [3, 4].

In order to achieve these tasks an optical fibre was laid connecting all PD bases located at the accessories throughout the tunnel. The achieved PD measuring sensitivities at the cable accessories were equivalent to laboratory conditions or even exceeding them.

The distributed PD measuring equipment was checked in three steps. Firstly, the internal test signal generators were successively activated, so as to verify full functional readiness of all 22 measuring channels. Secondly, via the 400 kV test bushing, calibration pulses of 500 pC were injected to the cable. To trace these calibration pulses along the 20 km cable route, it became necessary to average measurement data from the capacitive PD sensors. Without averaging, the calibration pulses were damped and soon vanished into the noise. The coherent averaging for all PD channels was based on the clock signal of the calibration pulse generator.

Using mean-value formation, this enabled the 500 pC calibration signal and its part-reflection at the next joint to be clearly distinguished from the background noise level even after a distance of 20 km [13]. In figure 8 the propagation of the calibration impulses along the cable system is shown for first three joints.

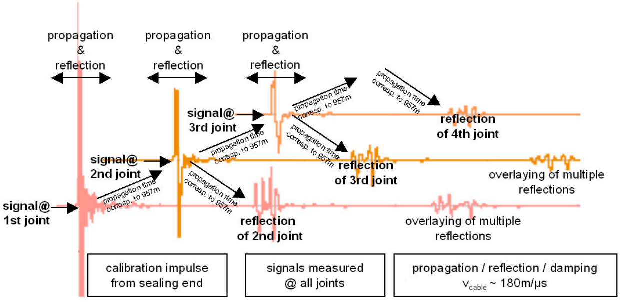

**Fig. 8 Propagation / reflection / damping of calibration pulses**

A reflection and propagation takes place at every joint due to a change from cable geometry to joint geometry establishing a change of the capacity at that point. The consequence is a jump of the impedance. The delay of arrival of the impulses corresponds to the different location of the PD bases. Over the entire cable system the calibration pulses were detectable at all accessories by means of mean-value formation. In addition to the main calibration signal after a certain time the reflection impulses can be observed at each location. The second impulse group represents an overlaying reflection of other reflections in the system, thus the width of pulses increases and becomes more uncertain. The number of these reflection groups decreases over the distance to the calibration source. On the first joint more or less five reflection events were observable, on the far end only one.

Figure 9 shows the change in the calibration pulse waveform recorded at different points along the cable system. At the point of injection the calibration pulse is very fast with an high amplitude. The pulse shape becomes broader and less intense with distance along the cable system.

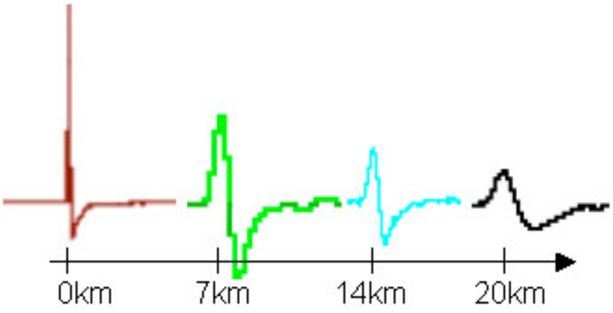

**Fig. 9 Change of impulse shape**

Due to the cable acting as a low pass, high frequency components of the signal are attenuated. This transformation takes place without loss off energy (area underneath the shape is constant). These basics of signal propagation theory were confirmed by performing an FFT transformation of the signals into a spectral depiction. The severe attenuation of higher-frequency signal components with distance from the in feed location of the calibration signals was clearly discerned.

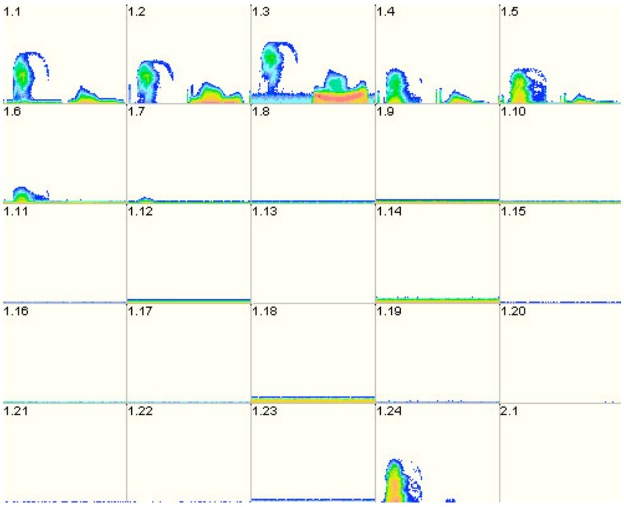

**Fig. 10 ”Wire test” : @ higher frequencies (6MHz)**

**PD base 1.1:** sealing end in Elstree
**PD base 1.2 & 1.3:** sealing end in Elstree (inductive sensor)
**PD base 1.4…1.23:** joints from Elstree to St. John´s Wood
**PD base 1.24:** sealing end in St. John´s Wood

The third and final step to test the function of the partial-discharge measuring equipment was a “wire test” immediately performed prior to each voltage test.

Here a standard laboratory test was performed by measuring the PDs from a copper wire is connected to the high voltage supply and directed to ground.

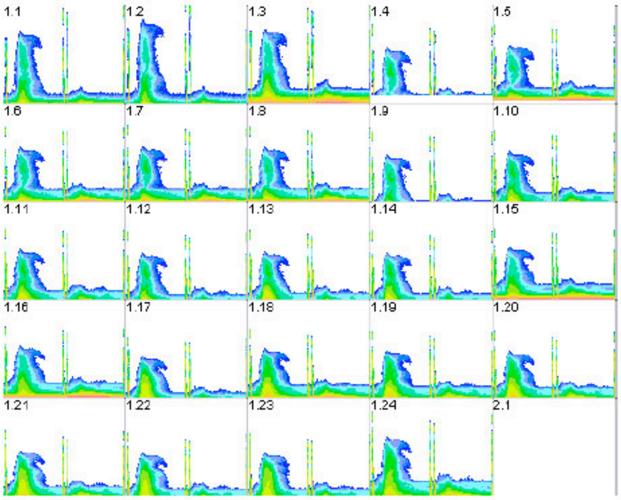

**Fig. 11 ”Wire test”: @ lower frequencies (600kHz)**

**PD base 1.1:** sealing end in Elstree
**PD base 1.2 & 1.3:** sealing end in Elstree (inductive sensor)
**PD base 1.4…1.23:** joints from Elstree to St. John´s Wood
**PD base 1.24:** sealing end in St. John´s Wood

The results of the “wire test” are given in the overviews in figures 10 and 11. In total 22 PD patterns represent the two sealing ends and 20 joints. PD stations 1.1, 1.2 and 1.3 were measured with one capacitive and two inductive PD sensors at the nearby (supply-side) $SF_6$ sealing end, and exhibit similar PD amplitudes to the wire test. The inductive sensors were introduced, in order to compare the results of the capacitive sensor with a newly developed inductive sensor.

The frequency-dependent attenuation of these PD signals can be highly advantageous for evincing the selectivity of PD measurements at the individual accessories. The user-settable mid-frequency of the PD measuring instruments was employed (factoring in the transmission bandwidth of the capacitive PD sensors) to set the measuring frequency to ensure that interference from the test set-up plays practically no role at all. Fig. 10 and 11 depict this influence of the measuring frequency. Fig. 10 shows the PD patterns of all PD stations at 6 MHz mid-frequency (exception: PD station 1.24 –$SF_6$ sealing end at St. Johns Wood– mid-frequency 1 MHz). PD stations 1.4, 1.5, 1.6 and 1.7 at the first four joints exhibit a steep decrease in PD amplitude with increasing distance from the supply side. As from PD station 1.8 (5th joint), only uniform background noise levels were measured. In figure 11, the mid-frequency was lowered to 600 kHz. The distance-dependent attenuation of the PD signals was reduced far enough to ensure that the PD patterns of the wire test at all cable accessories could still be clearly detected over the background noise level. At this measuring frequency, the four phase-locked interference pulses caused by the inverters of the resonance system also emerged quite prominently in all PD patterns.

## OUTLOOK

The combination of resonant AC voltage testing and distributed synchronous PD measurements at all cable accessories has also proved highly efficacious at the commissioning tests for this 20 km long extra-high-voltage cable system. The attenuation of external interference, which rises with increasing cable length, led to PD measuring sensitivities at the cable accessories equivalent to laboratory conditions or even exceeding them. Also for the supply-side cable sealing end where external interference signals act without any attenuation, the synchronous multi-channel PD measurements opened up new, significantly improved options for unambiguous PD assessment [11] compared to previous methods where selectivity could not be assured with any certainty.

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