Return to Session

DESIGN OF A 45 CIRCUIT DUCT BANK

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ABSTRACT

Bankside power station in London, closed in 1981 but the substation that is housed in the same building has remained operational. The remainder of the building has housed the Tate Modern art gallery since 2000. EDF Energy Networks is now engaged in a project to upgrade and modernise Bankside substation. Part of this work involves the diversion of about 45 cable circuits into a duct block within the basement of the substation. The circuits include pilot circuits, LV circuits and 11 kV, 22 kV, 66kV and 132 kV circuits. This paper describes the process involved in designing the duct bank.

KEYWORDS

Duct bank, Magnetic field, Surface temperature, Cable rating.

INTRODUCTION

Bankside power station, on the south bank of the Thames in London, closed in 1981 but the substation that is housed in the same building has remained operational. In 1995 work was started to transform part of the power station building into an art gallery, The Tate Modern, which was opened in 2000. EDF Energy Networks is now engaged in a project to upgrade and modernise the Bankside substation. Part of this work involves the diversion of about 45 cable circuits into a duct bank within the basement of the substation. The circuits include pilot circuits, LV circuits, 11 kV, 22 kV, 66kV and 132 kV circuits.

The proposed duct bank was to be approximately 100 m long over a width of 13 m with a depth of 1.2 m.

Because of potential future uses for the area above the duct bank there were a number of factors that had to be taken into account when designing the duct configuration and selecting the cable sizes to be used. These included:

- Maximum cable conductor temperature
- Floor surface temperature
- 50 Hz Magnetic field levels
- Cable routing requirements

The calculation methods used to design the duct bank were a mixture of traditional cable rating calculations, analytical calculations for floor surface temperatures and magnetic field levels and finite element methods to determine shielding requirements.

CIRCUIT REQUIREMENTS

The duct block was designed to carry the following XLPE insulated cable circuits without exceeding the operating temperature of any cable within the duct block.

- Four 400/230V circuits with a cyclic loading of 300A.
- Twenty 11kV circuits with a cyclic loading of 400A.
- Sixteen 20kV circuits with a cyclic loading of 400A
- Four 66kV circuits with a cyclic loading of 300A
- Two 132kV circuits with a cyclic loading of 700A
- Six pilot circuits.

The cyclic load was taken to be a step wave with 100 % load factor from 08.00hrs to 20.00hrs and 0.8pu from 20.00hrs to 08.00hrs.

The cables selected for this installation were of types commonly used by distribution companies in the UK. They were:

- 400 V, 3 or 4-core XLPE insulated, unarmoured, cables,
- 11 kV, Single-core cables laid in triplex formation generally to BS 7870-4.10,
- 20 kV, Single-core cables laid in triplex formation generally to BS 7870-4.10,
- 66 kV, Single-core, XLPE insulated cables with copper wire and aluminium foil screen,
- 132 kV, Single-core, XLPE insulated cables with copper wire and aluminium foil screen.

150 mm diameter plastic ducts to ENA Technical Specification 12-24 were selected.

The 132 & 66 kV circuits were to be installed in trefoil ducts and the other circuits were to be installed in single ducts.

RATINGS CALCULATIONS

Nominal Ratings

The first stage in the calculations was to obtain nominal single circuit, steady state, in duct, ratings for the cable types to be used in the installation.

The steady-state current ratings for the LV cables were taken from a base data used to develop ERA Report 69-30 Pt V, [1], those for the 11 kV cables were taken from the steady state section of Engineering Recommendation P17 Part 3, [2]. Nominal steady-state current ratings for the 20 kV, 66 kV and 132 kV cables were calculated, using the methods set out in IEC 60287, [3], from nominal cable dimensions provided by cable manufacturers. All of the current ratings were adjusted for an ambient temperature of 20°C and a soil thermal resistivity of 1.2 K.m/W. It was assumed that the cable screens would be solid bonded in all cases.

A general cyclic rating factor for the group was calculated using the equation given in Clause 3.2.2 of IEC 60853-1, [4]. Although the equations given in IEC 60853-2, [5], were more appropriate for the higher voltage cables the simpler approach of Part 1 was used for the initial calculations.

Cable selection

For the initial calculations it was assumed that the ducts would be installed in three tiers with a horizontal spacing of 600 mm and a vertical spacing of 500 mm. The only limitation on the location of cables within the duct bank was that the 132 kV circuits should be near the sides of the duct bank. This limitation was imposed by the route of the existing cables.

The initial selection of cable sizes was achieved by assuming that a grouping factor of 0.7 would be applicable to the group.

The temperature rise at each cable due to the heat dissipated by all of the other cables was then calculated using the method set out in IEC 60287-2-1 Clause 2.2.3.1. The equation used to calculate these temperature rises, $\Delta\theta_p$, was:

$$\Delta\theta_p = \Delta\theta_{1p} + \Delta\theta_{2p} + \cdots \Delta\theta_{kp} + \cdots \Delta\theta_{qp} \qquad [1]$$

Where:

$$\Delta\theta_{kp} = \frac{1}{2\pi}\rho_T W_k \, ln\left(\frac{d'_{pk}}{d_{pk}}\right)$$

$\Delta\theta_{kp}$ = temperature rise at cable p due to heat dissipated by cable k,
ρ_T = thermal resistivity of backfill,
W_k = power dissipation from cable k,
d'_{pk} = distance from cable p to the reflection of cable k in the ground-air interface,
d_{pk} = distance from cable p to cable k .

The temperature rise of each cable due to the load it carried was calculated on the basis that this temperature rise was proportional to the square of the load current. This was added to $\Delta\theta_p$ and the ambient temperature to determine the conductor temperature for each cable.

These initial calculations demonstrated that many of the cables selected would run at more than 90°C. This was not acceptable and showed that the assumption of a grouping factor of 0.7 was overly optimistic.

The calculation method was based on the mutual heating between circuits. Because of this the conductor size selected for one circuit will influence the conductor temperature, and hence the selection of sizes, for surrounding circuits. Thus it would have been possible to select different conductor sizes for each circuit to arrive at a solution where none of the cables would be operating at higher than 90°C. However it was not considered practical to specify which cable size should be installed in each duct. To simplify the final installation it was decided that only one conductor size would be used for each voltage group.

After several iterations, with increased conductor sizes, it was concluded that an acceptable solution could not be reached with the duct arrangement chosen.

The duct arrangement was then changed so that the ducts in the top layer were on 400 mm centres and the ducts in the lower 2 layers were staggered with 800 mm between centres. Eight trefoil ducts were arranged on the lower layers to accommodate the 132 & 66 kV circuits and allow 2 spares.

With the new cable arrangement lower temperatures were achieved but an acceptable solution still could not be found.

The initial data was then revisited and it was decided that because the ducts were to be surrounded with concrete it was reasonable to use a lower value of thermal resistivity for the surrounding medium. A value of 1 K.m/W was used for the next iteration.

An acceptable solution was achieved where none of the cables exceeded their maximum operating temperature of 90 °C. However the conductor size required for the 132 kV cables was considered to be excessive and the triplex 22 kV cables had an outside diameter that was close to the duct size. In order to reduce the size of the 132 kV cables the effect of single-point bonding was investigated. Also the effect of the cyclic load was considered in greater detail. For the next calculations the cyclic rating factor was calculated for each cable based on the method set out in Clause 7.3 of IEC 60853-2.

The final solution gave the cable conductor temperatures listed in Table 1 with the duct layout shown in Fig. 1.

Return to Session

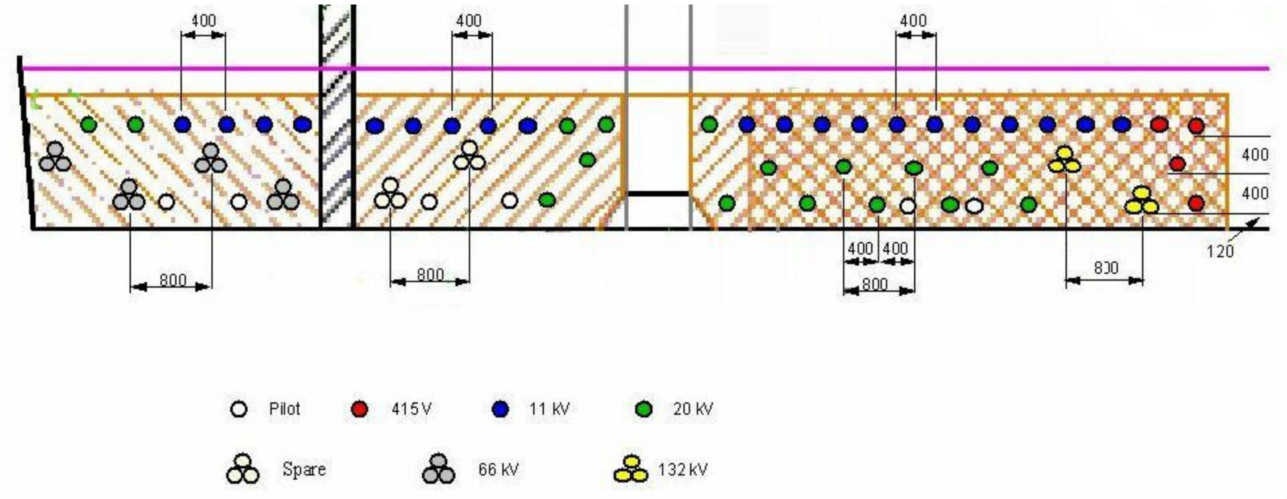

Figure 1 Duct layout

Table 1 Cable temperatures

Circuit	Temperature °C	Circuit	Temperature °C
400 V, 1	82	**20 kV**, 1	53
2	75	2	55
3	82	3	82
4	81	4	76
11 kV, 1	70	5	55
2	71	6	53
3	71	7	55
4	69	8	77
5	72	9	78
6	75	10	86
7	74	11	82
8	73	12	89
9	70	13	84
10	72	14	90
11	74	15	84
12	75	16	90
13	75	**66 kV**, 1	61
14	75	2	71
15	76	3	73
16	76	4	79
17	76	**132 kV**, 1	86
18	77	2	85
19	76		
20	73		

The temperatures in Table 1 show that many of the cables will be operating at 10 to 20 °C below their maximum permitted operating temperature. It is inevitable in any large group of cables that not all of the cables can be fully utilised.

It is also noted that the solution that has been arrived at is not the only solution for this number of circuits. Increasing the conductor size in one voltage group could allow the conductor size to be reduced in another voltage group. Also moving ducts closer together or further apart will influence the calculated temperatures. However it was considered that adopting a relatively simple duct arrangement with regular spacings would lead to a simpler installation.

FLOOR SURFACE TEMPERATURE

The calculations described above are based on the method given in IEC 60287. This method is based on the assumption that all of the heat generated by buried cables is dissipated from the surface of the ground. Thus the heat generated by the cables in the duct bank will be dissipated from its upper surface. This will lead to a noticeable temperature rise at the surface of the floor above the duct bank.

A method of calculating the temperature rise of the soil surface above a buried cable when the surface is not an isotherm is given by King & Halfter, [6]. In this method the thermal resistance between the soil surface and the surroundings is calculated. The thickness of a soil layer that would provide the same thermal resistance is then calculated. A 'fictitious' layer of soil of this thickness is then added to the surface and the temperature at the interface between the fictitious layer and the real surface is calculated. The thickness of this fictitious layer, δ, is calculated from:

$$\delta = \frac{1}{\alpha \rho_T}$$

Where:
α = Soil/air heat transfer coefficient, a value of 10 W/K.m² was used in the calculations.

This method was used to calculate the temperature rise at the surface of the duct bank due to the heat dissipated by each cable. The temperature at any point on the surface was taken to be the sum of these temperature rises, plus ambient temperature. The temperature was calculated for a series of points along the width of the duct bank. A plot of the calculated floor temperature above the cable duct bank for several loading situations is shown in Fig. 2.

The maximum predicted floor temperature at 100 % load was 34°C. The 100% curve assumes that all of the cables are carrying the design loads. The 75 % and 50 % curves assume that all of the cables are carrying a percentage of the design load. The calculated floor temperature with the conductor size for the 11 kV cables increased by 3 sizes and those for the 20 kV cables increased by one size is shown in Fig. 3

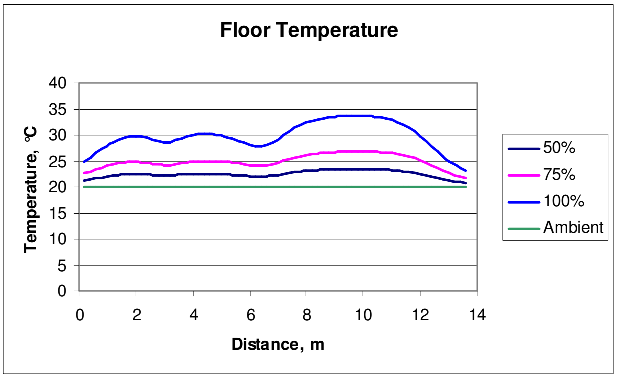

Figure 2 Temperature profile with chosen cables

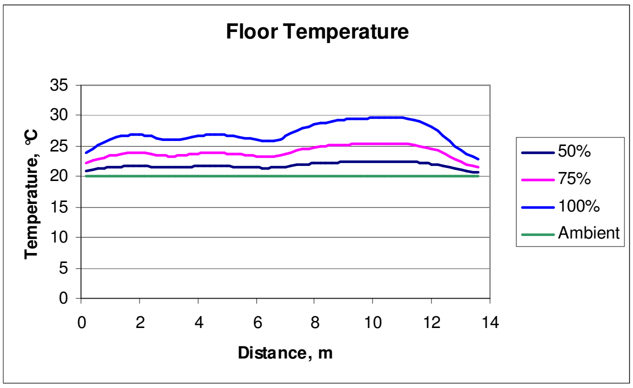

Figure 3 Temperature profile with larger cables

The maximum predicted floor temperature at full load is about 10 °C higher than the limit initially specified. Increasing the size of the 11 kV and 22 kV cables would reduce the maximum predicted floor temperature to approximately 20 °C for 100 % loading and just over 25 °C for 75% loading. However these increases in cable size were not considered practical because of the limitations in duct size.

Other options to reduce the floor temperature included installing water-cooling or a forced air flow through a void between the top of the duct bank and a raised floor. Further consideration of these options was outside the scope of the project. Thermal insulation cannot be installed between the top of the duct bank and the new floor to limit the floor temperature because this would severely restrict the heat loss from the duct bank.

MAGNETIC FIELD

In April 1998, the International Commission on Non-Ionising Radiation Protection (ICNIRP) published guidelines for limiting exposure to electromagnetic fields in the frequency range from dc up to 300GHz. The reference levels given by ICNIRP are presented in a two-tier system, one set of levels for occupational exposures and the other set for general public exposures. The ICNIRP magnetic field Reference Level for workers is 500 µT and that for the general public is 100 µT.

Experience has shown that 50 Hz magnetic fields in excess of 1 µT causes interference on most CRT computer monitors, which typically leads to a horizontal flickering of the image. 50 Hz magnetic fields do not cause flicker on 'flat screen' monitors.

In the initial specification for the calculations a maximum 50 Hz magnetic field level of 0.3 µT above the duct bank was specified.

Because of these requirements calculations were carried out to determine the expected 50 Hz magnetic field at several heights above the floor and the effectiveness of screening in reducing the magnetic field. These calculations involved a combination of analytical and finite element analysis.

The magnetic field at a given distance from a current carrying conductor is given by:

$$B = \frac{\mu_0 I}{2\pi L} \qquad [2]$$

Where:
μ_o = permeability of free space, T.m/A, = $4\pi \times 10^{-7}$
I = current, A
L = distance from the source, m.

In a three-phase cable the current in each phase is taken to be 120 ° out of phase with each other. Hence the magnetic fields will also be out of phase. Thus if the distance from each conductor to the point of interest was the same there would be complete cancellation of the magnetic field at the point of interest. However each conductor will be a different distance from the point of interest and hence there will be a residual magnetic field.

This principle was used to calculate the magnetic field from each cable in the duct bank. The position of each conductor was defined in terms of X – Y co-ordinates as was the position of the point of interest. The magnetic field from the conductors of each cable was calculated as a vector quantity for a series of different positions across the width of the duct bank. The magnetic field at each point was then taken as the magnitude of the sum of these vector quantities.

The phase angle of the vector is a function of the relative distance of the 3 phases from the point of interest. If the U phase is closest to the point of interest then the phase angle of the U phase will predominate. If in an adjacent circuit the V is closest then the phase angle of the V phase will predominate. Thus the magnitude of the vector sum is a function of the phase positions in each duct. The highest magnetic field will be if all of the cores of one phase are at the same position in the ducts. Because the positions of the phases in the ducts containing 3-core or triplex cables cannot be defined the magnetic field has been calculated for 2 conditions; one with the same phase at the same position in each duct and the other with the phases rotated by one position in each adjacent duct. For both conditions it has been assumed that there will be phase rotation of the 132 and 66 kV circuits between adjacent trefoil ducts. The actual magnitude of the magnetic field is expected to be between these two values.

For solidly bonded cables the circulating current in the screens will generate a magnetic field that opposes that developed by the phase conductors. This will reduce the overall magnetic field from each cable. Because the circulating currents are expected to be small relative to the phase currents this reduction will be small and it has been ignored.

The calculated magnetic field across the width of the duct bank for the condition that was considered to be the worst case is shown in Fig. 4. In this case the maximum 50 Hz magnetic field was approximately 30 µT at floor level and 11 µT at 1 m above the floor.

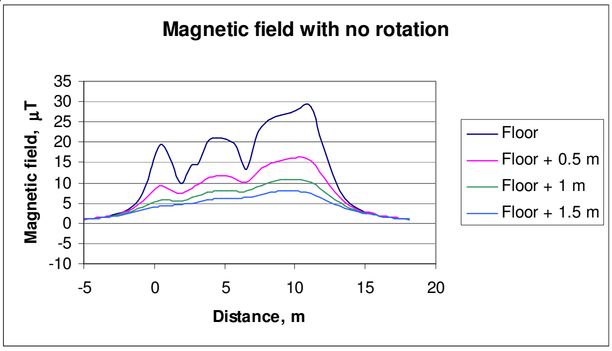

Figure 4 Predicted magnetic fields with no 'rotation'

For the 'best' case condition the maximum calculated magnetic field was approximately 12 µT at floor level and 2.5 µT at 1 m above the floor, Fig. 5.

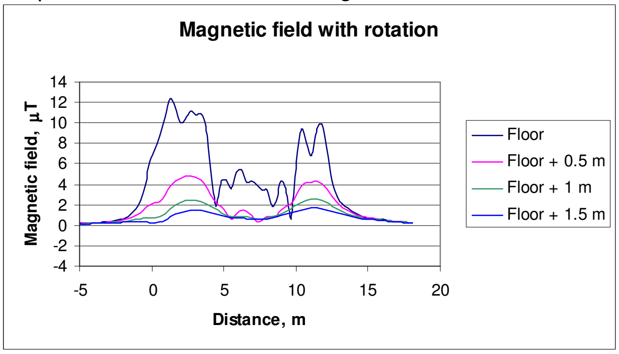

Figure 5 Predicted magnetic fields with 'rotation'

Although the calculated magnetic field levels are below the ICNIRP Reference Level, for public exposure, of 100 µT they are high enough to cause interference on CRT computer monitors. Because of this, the effect of screening was considered.

The form of shielding that was considered was a steel screen that would cover the top of the duct bank, run down the sides and extend part way under the duct bank. It was recognised that if the shield did not completely surround the cables or was not continuous the magnetic field would 'leak' around the shield or through the gaps. This was the reason for extending the shield down the sides of the duct bank. The possibility of using steel pipes in place of the plastic ducts was rejected because induced eddy currents in the steel pipes would add to the heat generated in the duct bank.

A finite element model was used to assess the effectiveness of limited shielding around the duct bank. To avoid the complexity of building a model containing all 46 circuits and reduce the run time of the model, a simple model was built containing 6 cables and the cable loading and positions adjusted so that the magnetic field at 1 m above these cables was similar to the value obtained from the analytical calculations, with no shielding.

The steel property that affects its shielding properties is the relative permeability. For steel manufactured in the thickness needed for shielding against magnetic fields this property is not controlled. The value could be anywhere between about 300 and 1000. The lower value was used in the design calculations.

The model was run with 8 mm thick steel shielding only over the top of the duct bank. The results of this run confirmed that the maximum field occurred close to the edges of the shield where the field was 'leaking' past the screen. This maximum value was about 60 % of the maximum value calculated without shielding, 7.4 µT in the best case. Further shielding was then added to the model extending down both sides of the duct bank and underneath it for a distance of 1 m from the edges. With this screening the best case calculated field above the duct bank was reduced to 1.5 µT at floor level. Further finite element estimates indicated that adding a second layer of 8 mm thick steel would reduce the magnetic field level to about 0.3 µT at floor level in the best case.

The above calculations have not taken any account of 'leakage' of the magnetic field at joints in the screening plates or the practical difficulties of screening the cables at the ends of the duct bank. To prevent leakage at the joints in the screening the plates would either have to be welded or have additional plates bolted over the joints. In both cases this would result in a large floor area of steel that would be subjected to temperature fluctuations, and hence thermal expansion and contraction, as the loading in the cable circuits varied. One option for avoiding the stresses that thermal expansion of the steel may produce would be to lay the shielding as 3 layers of loose 6 mm steel plate with overlapping joints. This would minimise the leakage at joints by giving a minimum of 6 mm of screening while allowing gaps between the plates to accommodate any thermal movement.

CONCLUSIONS

The calculations have shown that the required number of circuits and loads can be accommodated within the space available for the duct bank.

With the cable sizes selected to comply with the maximum permitted conductor temperatures the calculated floor surface temperature is approximately 35 °C with all the circuits loaded. Increasing the conductor size of the 11 kV and 20 kV cables to 630 mm² would reduce the maximum predicted floor temperature to 30 °C however the duct sizes would have to be increased to accommodate these larger cables.

Calculation of the 50 Hz magnetic field level above the duct bank has shown that the level is less than the NRPB/ICNIRP reference level for public exposure. It is estimated that screening the top, sides and part of the base of the duct bank with 8 mm thick steel plate would reduce the magnetic field to less than 2 μT at floor level. Further estimations indicate that installing two layers of 8 mm plate would reduce the magnetic field at floor level to about 0.3 μT. However particular attention would have to be given to how the screening plates are joined to avoid problems associated with thermal expansion of the steel plates.

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