From: [redacted]
To: Hornsea Project Three
Cc: [redacted]
Subject: Open Floor Hearing 25th March 2019 - WRITTEN SUBMISSION - HORNSEA PROJECT THREE OFFSHORE WIND FARM
Date: 26 March 2019 00:57:44
Attachments: Open Hearing Response 25 Mar 19.docx
Attachment 1.pdf
Attachment 2.pdf
Attachment 3.pdf
Attachment 4.pdf
Attachment 5.pdf
Attachment 6.docx
Graphic 1 to 25 Mar 19.docx

Our Reference: 20010156
Your Reference: EN010080

Dear Planning Inspectorate,

Please find attached our written submission to supplement the oral representation from the Open Floor Hearing on 25th March 2019, including relevant Attachments and Graphics.

Thank you for the opportunity to make representations on the project.

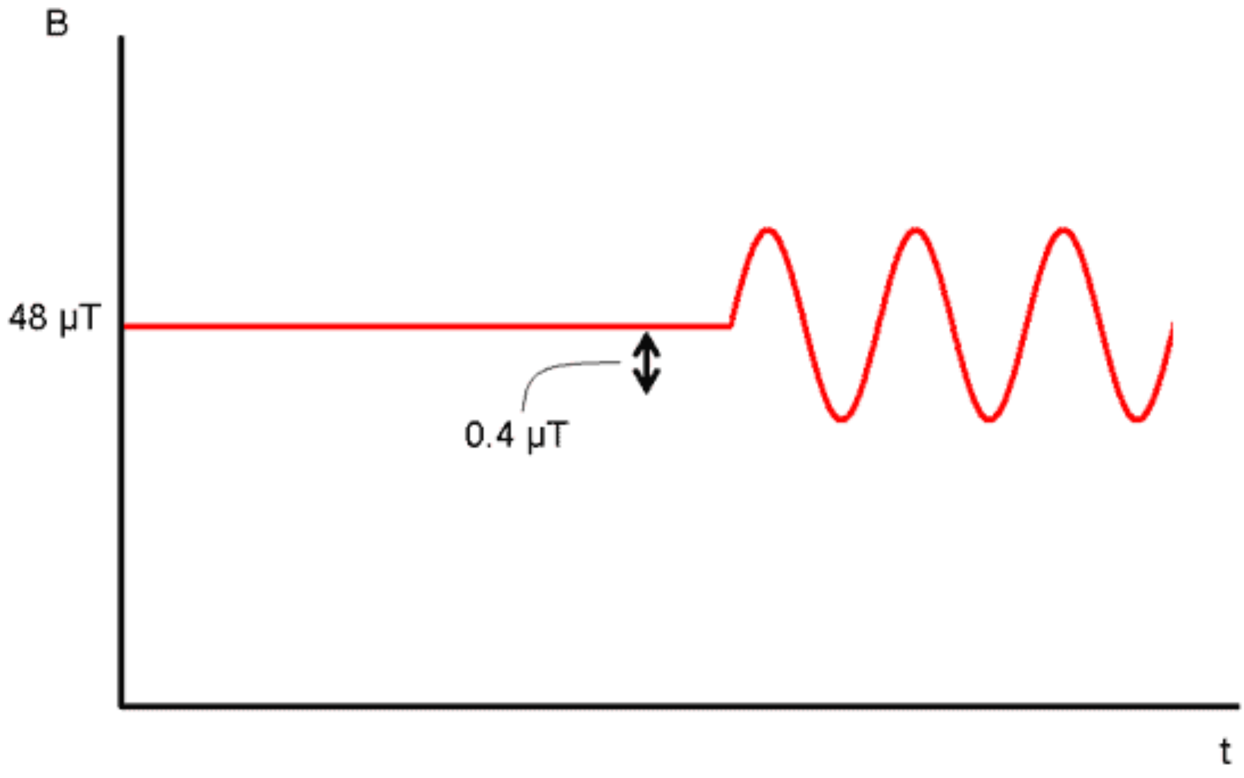
Yours faithfully,

Ray & Diane Pearce

Total field and AC field

How do AC and DC fields relate to each other?

We live in a DC magnetic field, the earth's geomagnetic field, and any AC field is superimposed on it.



The AC field is often less than the DC field. In fact it's often very much less. This example, not drawn to scale, shows the 0.4 μT AC field implicated in the epidemiology of childhood leukaemia with the typical 48 μT geomagnetic field in the UK. (0.4 μT is the rms value, the peak is slightly higher, see a tutorial on ways of characterising AC fields.)

When the AC field is less than the DC field, it doesn't change the average value of the total field. The AC fluctuations average to zero, and the average field is still 48 μT in this example.

What does this mean for mechanisms?

Let's consider proposed mechanisms for how an AC magnetic field might produce effects in living systems. Clearly, if a mechanism depends just on the AC component, the DC field and the total field are irrelevant. Induced currents, for example, are produced only by AC fields.

But some mechanisms depend on the total field. The free radical mechanism is one example. It operate on such a fast timescale - tens of nanoseconds - that it just "sees" the instantaneous total field without knowing whether that is an AC field or a DC field.

If these mechanisms that depend on the total field were strictly linear - the effects they produced was exactly proportional to the field - any effects of the AC field produced would also average to zero. On the positive half cycle there would be a positive effect, on the negative half cycle an equal and opposite negative effect, and the two cancel. For free radicals, it might be an increase in the concentration on the positive half cycle and an equal and opposite decrease on the negative half cycle. The average concentration of free radicals is unchanged.

The only way these mechanisms can produce an overall effect from an AC field is if they are not strictly linear. Then the effect on the positive half cycle might be slightly larger than the effect on the negative half cycle, and the two would not exactly cancel, leaving a small overall effect.

This has two consequences.

- because the effect arises from the imperfect cancellation of two opposite effects, it is expected to be a smaller effect; and

- mathematically, we are saying that the linear component still averages to zero, and the net effect comes from the non-linearity, which is expressed as a quadratic or square term. So any effect of AC fields from these mechanisms will dependent not on the field but on the field squared (or, in principle, an even higher power).

We also predict, for mechanisms that depend on the total field, that if the AC field produces effects, then so would changes in the DC field, for example as we move from one lattitude to another on the earth. See one test of the implications of this for epidemiology.

See also:

- What are DC fields?
- Are there health effects associated with DC?

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Free radicals

A candidate mechanism for the interaction of magnetic fields with living systems

Some biological molecules can be split into two free radicals - reactive species with single, unpaired electrons and therefore a spin. Whether they recombine or stay separate depends on whether the two spins change direction or not. A magnetic field can change the spins. So this is a mechanism whereby magnetic fields can affect the outcome of a chemical reaction and change the concentrations of these reactive species.

For this to happen, there has to be the right combination of conditions: the recombination time, the strength of the external magnetic field compared to internal magnetic fields, and so on. The effect has been demonstrated many times at relatively high fields, a mT or more. But it hasn't yet been demonstrated at the lower fields, of order a microtesla, implicated by the epidemiology. Research continues (including by the EMF Biological Research Trust, which has pioneered this area), but free radicals can not yet be regarded as a plausible mechanism.

There is also another reason why it seems that this mechanism cannot underlie the epidemiological results. Free-radical reactions typically have timescales of tens of nanoseconds, compared to which 50 Hz fields are effectively static. The relevant magnetic field is therefore the instantaneous total field, which is usually dominated not by the power-frequency component but by the geomagnetic field, which is around 50 μT in the UK. See more discussion of this issue and a test of one of the implications.

See also:

- One particular candidate molecule for the action of the free-radical mechanism is the cryptochromes.
- See further discussion on plausibility of mechanisms and other candidates.

Latest news

How has the reported risk for childhood leukaemia changed over time? February 11, 2019

Media stories about microshocks in children's playground September 10, 2018

New studies on leukaemia and distance from power lines June 1, 2018

UK media interest in the causes of childhood leukaemia May 22, 2018

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Electromagnetic fields 2007

The Biological Effects of Weak Electromagnetic Fields

Andrew Goldsworthy 2007

What the power and telecoms companies would prefer us not to know

Foreword

There have been many instances of harmful effects of electromagnetic fields from such seemingly innocuous devices as mobile phones, computers, power lines and domestic wiring. They include an increased risk of cancer, loss of fertility and unpleasant physiological symptoms. The power and mobile phone companies, hoping to avoid litigation, often assert that because the energy of the fields is too low to give significant heating, they cannot have any biological effect. However, the evidence that electromagnetic fields *can* have "non-thermal" biological effects is now overwhelming. In this article, I will explain how these effects arise. I have included key references that should enable the more inquisitive reader to delve deeper. If you do, you will often find contradictory assertions and that the reproducibility of several experiments is only mediocre. As we will see, this is almost certainly because of differences in the genetic and physiological condition of the biological material and its ability to defend itself against electromagnetic insults. Defence mechanisms have evolved by natural selection over countless millions of years of exposure to natural electromagnetic radiation, such as that from thunderstorms. They can often hide the underlying effects of man-made fields so we do not always see them in our experiments. We therefore have to concentrate on the experiments that give positive results if we are to discover the mechanisms. In this context, negative findings (frequently published in work financed by the telecoms and power companies) have no meaning.

Abstract

1. Well-replicated studies have shown that weak electromagnetic fields remove calcium ions bound to the membranes of living cells, making them more likely to tear, develop temporary pores and leak.

2. DNAase (an enzyme that destroys DNA) leaking through the membranes of lysosomes (small bodies in living cells packed with digestive enzymes) explains the fragmentation of DNA seen in cells exposed to mobile phone signals. When this occurs in the germ line (the cells that give rise to eggs and sperm), it reduces fertility and predicts genetic damage in future generations.

3. Leakage of calcium ions into the cytosol (the main part of the cell) acts as a metabolic stimulant, which accounts for reported accelerations of growth and healing, but it also promotes the growth of tumours.

4. Leakage of calcium ions into neurones (brain cells) generates spurious action potentials (nerve impulses) accounting for pain and other neurological symptoms in electro-sensitive individuals. It also degrades the signal to noise ratio of the brain making it less likely to respond adequately to weak stimuli. This may be partially responsible the increased accident rate of drivers using mobile phones.

5. A more detailed examination of the molecular mechanisms explains many of the seemingly weird characteristics of electromagnetic exposure, e.g. why weak fields are more effective than

strong ones, why some frequencies such as 16Hz are especially potent and why pulsed fields do more damage.

Introduction

The strange non-thermal biological effects of electromagnetic fields have puzzled scientists for decades and, until now, there has been no clear explanation. In this article, I will outline a new theory, based on experimental evidence gathered over many years, that explains how virtually all of these effects arise.

Firstly, it is not only humans that are affected. Well-researched responses in other organisms include the more rapid growth of higher plants (Smith et al. 1993; Muraji et al. 1998; Stenz et al. 1998), yeast (Mehedintu and Berg 1997) and changes in the locomotion of diatoms (McLeod et al. 1987). The last two are significant because they are both single cells, implying that the effects occur at the cellular level. Furthermore, we can explain virtually all of the electromagnetic effects on humans in terms of changes occurring at the cellular level that may then affect the whole body.

A few basic facts

Field strength: - An electromagnetic field consist of an electrical part and a magnetic part. The electrical part is produced by a voltage gradient and is measured in volts/metre. The magnetic part is generated by any flow of current and is measured in tesla. For example, standing under a power line would expose you to an electrical voltage gradient due to the difference between the voltage of the line (set by the power company) and earth. You would also be exposed to a *magnetic* field proportional to the current actually flowing through the line, which depends on consumer demand. Both types of field give biological effects, but the magnetic field is more damaging since it penetrates living tissue more easily. Magnetic fields as low as around one microtesla (a millionth of a tesla) can produce biological effects. For comparison, using a mobile (cell) phone or a PDA exposes you to magnetic pulses that peak at several tens of microtesla (Jokela et al. 2004; Sage et al. 2007), which is well over the minimum needed to give harmful effects. Because mobile phones are held close to the body and are used frequently, these devices are potentially the most dangerous sources of electromagnetic radiation that the average person possesses.

Frequency: - The fields must vary with time, e.g. those from alternating currents, if they are to have biological effects. Extremely low frequencies (ELF) such as those from power-lines and domestic appliances are more potent than higher frequencies. There is usually little or no biological response to the much higher frequencies of radio waves, unless they are *pulsed* or *amplitude modulated* at a biologically active lower frequency (i.e. when the radio signal strength rises and falls in time with the lower frequency). Regular GSM mobile phones and PDAs emit both pulsed radio waves (from the antenna) and ELF (from the battery circuits), and are especially dangerous. So how do these non-thermal effects electromagnetic fields arise?

Weak electromagnetic fields release calcium from cell membranes

The first clue came from Suzanne Bawin, Leonard Kaczmarek and Ross Adey (Bawin et al. 1975), at the University of California. They found that exposing brain tissue to weak VHF radio signals modulated at 16Hz (16 cycles per second) released calcium ions (electrically charged calcium atoms) bound to the surfaces of its cells. Carl Blackman at the U.S. Environmental Protection Agency in North Carolina followed this up with a whole series of experiments testing different field-strengths and frequencies (Blackman et al. 1982) and came to the surprising conclusion that weak fields were often more effective than strong ones. The mechanism was unknown at the time and it was thought to be a trivial scientific curiosity, but as we will see, it has huge significance for us all.

The loss of calcium makes cell membranes leak

Calcium ions bound to the surfaces of cell membranes are important in maintaining their stability. They help hold together the phospholipid molecules that are an essential part of their make-up (see Ha 2001 for a theoretical treatment). Without these ions, cell membranes are weakened and are more likely to tear under the stresses and strains imposed by the moving cell contents (these membranes are only two molecules thick!). Although the resulting holes are normally self-healing they still increase leakage while they are open and this can explain the bulk of the known biological effects of weak electromagnetic fields.

Membrane leakage damages DNA

Leaks in the membranes surrounding lysosomes (tiny particles in living cells that recycle waste) can release digestive enzymes, including DNAase (an enzyme that destroys DNA). This explains the serious damage done to the DNA in cells by mobile phone signals. Panagopoulos et al. (2007) showed that exposing adult *Drosophila melanogaster* (an insect widely used in genetic experiments) to a mobile phone signal for just six minutes a day for six days broke into fragments the DNA in the cells that give rise to their eggs and half of the eggs died. Diem et al. (2005) also found significant DNA fragmentation after exposing cultured rat and human cells for 16 hours to a simulated mobile phone signal. See also the "Reflex Project" in an on-line brochure entitled "Health and Electromagnetic Fields" published by the European Commission. You can find it at http://tinyurl.com/yxy4ld . It shows that exposing human cells for 24 hours to simulated mobile phone signals gave DNA fragmentation similar to that due to the gamma rays from a radioactive isotope! (Gamma rays also make lysosome membranes leak).

DNA damage may cause cancer

There have been many studies suggesting that exposure to weak electromagnetic fields is associated with a small but significant increase in the risk of getting cancer (Wilson et al. 1990). This could be caused by gene mutations resulting from DNA damage. A gene is a section of DNA containing the information needed to make a particular protein or enzyme. There is also a section that can turn the gene on or off in response to outside signals. The growth of an organism from a fertilised egg involves a hugely complex pattern of switching genes on and off that regulates growth, cell division and differentiation into specific tissues. DNA damage can sometimes give unregulated growth to form tumours. However, the effect may not be immediate. Cancer following exposure to chemical carcinogens such as asbestos may take many years to become rampant. The affected cells seem to go through several stages of ever-increasing genetic and molecular anarchy before they finally reach the point of unstoppable growth and division. When assessing any carcinogenic effects of electromagnetic exposure, we must bear in mind that there may be a similar delay. It may be some years before we know the full carcinogenic effects of the recent explosive growth in the use of mobile phones.

DNA damage reduces fertility

The biological effects of electromagnetically induced DNA fragmentation may not be immediately obvious in the affected cells, since fragments of broken DNA can be rejoined and damaged chromosomes (elongated protein structures that carry the DNA) can be reconstituted. However, there is no guarantee that they will be rejoined exactly as they were. Pieces may be left out (deletions) joined in backwards (inversions) swapped between different parts of the chromosome (translocations) or even attached to the wrong chromosome. In most cases, the new arrangement will work for a while if most of the genes are still present and any metabolic deficiencies can often be made good by the surrounding cells. However, things go badly wrong when it comes to meiosis, which is the process that halves the number of chromosomes during the formation of eggs and sperm.

During meiosis, the chromosomes line up in pairs (one from each original parent) along their entire length so that corresponding parts are adjacent and can be exchanged (this gives each of the daughter cells a unique combination of genes). However, if the arrangement of their genes has been altered by electromagnetic exposure, they cannot align properly and the chromosomes may even tie themselves in knots in the attempt. Such mal-formed pairs are usually torn apart unequally in the later stages of meiosis so that the eggs or sperm have an incomplete or unbalanced set of genes, may not function properly and so reduce fertility. There is evidence from several independent studies in Australia, Hungary and the United States that this is already occurring. Heavy mobile phone use appears to reduce both the quantity and viability of sperm. The results for the most recent study by Dr Ashok Agarwal and co-workers at the Cleveland Lerner College of Medicine can be seen at http://tinyurl.com/28rm6n . They found that using a mobile phone for more than four hours a day was associated with a reduction in sperm viability and mobility of around 25 percent. The statistical probability of these results being due to chance errors was one in a thousand. There is every reason to believe that human *eggs* may be similarly affected, but since they are formed in the embryo before the baby is born, the damage will be done during pregnancy but will not become apparent until the child reaches puberty.

There may also be permanent genetic damage

Believe it or not, the electromagnetically induced loss of fertility is the *good news* since it means that badly damaged embryos are less likely to be conceived. The *bad news* is that any damaged genes needed for embryo development but not for normal egg or sperm function will not be weeded out in this way. They can still find their way into the foetus and cause permanent genetic damage. The effect may not be apparent in the first generation since a non-functioning gene from one parent can often be offset if the other parent provides a good version of the same gene. In fact, serious trouble may not arise for many generations until by chance two faulty versions of the same gene end up in the same foetus. What happens then depends on the gene concerned, but it is unlikely to be beneficial and may be lethal.

The overall conclusion is that the genetic damage from exposure to electromagnetic radiation can have an almost immediate effect on fertility, but damage to the offspring may take several generations to show up. If we do nothing to limit our exposure to electromagnetic radiation, we can anticipate a slow decline in the viability of the human genome for many generations to come. It is ironic that having only just discovered the human genome, we have already set about systematically destroying it.

Effects on metabolism

Another major effect of electromagnetic radiation is the leakage of *free* calcium ions, either through the cells' external membranes or those surrounding internal "calcium stores". This can have dramatic effects on many aspects of metabolism and explains most of the mysterious but well-documented physiological effects of electromagnetic fields. These include stimulations of growth, an increased risk of cancer, symptoms suffered by electrosensitive humans and why using a mobile phone while driving makes you four times more likely to have an accident.

How calcium controls metabolism

Apart from its role in maintaining membrane stability, the calcium concentration actually inside cells controls the rate of many metabolic processes, including the activity of many enzyme systems and the expression of genes. The concentration of calcium ions in the cytosol (the main part of the cell) is normally kept about a thousand times lower than that outside by metabolically-driven ion pumps in its membranes. Many metabolic processes are then regulated by letting small amounts of calcium into the cytosol when needed. This is normally under very close metabolic control so that everything works at the right time and speed. However, when electromagnetic exposure increases membrane leakiness, unregulated amounts of extra calcium can flood in. Just what happens then depends on how much gets in and what the cells are currently programmed to do. If they are growing, the rate of growth may be increased. If they are repairing themselves after injury, the rate of healing may be increased but if there is a mutant precancerous cell present, it may promote its growth into a tumour.

Calcium leakage and brain function

Normal brain function in humans depends on the orderly transmission of signals through a mass of about 100 billion *neurones*. Neurones are typically highly branched nerve cells. They usually have one long branch (*the axon*), which carries electrical signals as *action potentials* (nerve impulses) to or from other parts of the body or between relatively distant parts of the brain (a nerve contains many axons bundled together). The shorter branches communicate with other neurones where their ends are adjacent at *synapses.* They transmit information across the synapses using a range of *neurotransmitters,* which are chemicals secreted by one neurone and detected by the other. The exact patterns of transmission through this network of neurones are horrendously complex and determine our thoughts and virtually everything we do.

Calcium plays an essential role in this because a small amount of calcium must enter the neurone every time before it can release its neurotransmitters. Without it, the brain would be effectively dead. But what would happen if electromagnetically induced membrane leakage let in too much calcium? One effect would be to increase the background level of calcium in the neurones so that they release their neurotransmitters sooner. This improves our reaction time to simple stimuli (which has been experimentally proven). However, it can also trigger the spontaneous release of neurotransmitters to transmit spurious signals have no right to be there. This feeds the brain false information. Similar spurious action potentials may also be triggered in other parts of the neurone if leaks in the membrane temporarily short-circuit the normal voltage between its inside and outside. These unprogrammed action potentials will degrade the signal to noise ratio of the brain and reduce its ability to make accurate judgements.

It is technically difficult to detect these stray action potentials experimentally since they look like random noise in the measuring system and would in any case be swamped by the relatively strong electromagnetic signals used to induce them. However, similar spurious action potentials should be detectable if we removed some of structural calcium from the membrane by some other means. One way to do this is to lower the concentration of calcium ions in the surrounding medium. For example, Matthews (1986) reported that exposing nerve and muscle cells to calcium concentration about 10–20 percent below normal made them significantly more excitable, which fits with our hypothesis.

These findings also explain many of the symptoms of hypocalcemia (alias hypocalcaemia). Hypocalcemia is a medical condition, usually caused by a hormone imbalance, in which the concentration of ionised calcium in the blood is abnormally low. By removing bound calcium from cell membranes, it should (and does) give similar effects to electromagnetism.

Electrosensitivity and hypocalcemia – a possible cure

Symptoms of hypocalcemia include skin disorders, paresthesias (pins and needles, numbness, sensations of burning etc.) fatigue, muscle cramps, cardiac arrhythmia, gastro-intestinal problems and many others. A more comprehensive list can be found at http://tinyurl.com/2dwwps , which corresponds to the website: - http://www.endotext.org/parathyroid/parathyroid7/parathyroid7.htm.

The symptoms of hypocalcemia are remarkably similar to those of electrosensitivity. If you think you may be electrosensitive, how many of these do you have? If you have any of them, it may be worth having your blood checked for ionised calcium. It is possible that at least some forms of electrosensitivity could be due to the victims having their natural blood calcium levels bordering on hypocalcemia. Electromagnetic exposure would then remove even more calcium from their cell membranes to push them over the edge and give them symptoms of hypocalcemia. If this is correct, conventional treatment for hypocalcaemia may relieve some if not all of these symptoms.

Electromagnetic exposure and motor accidents

Only a small proportion of the population is electrosensitive in that they show obvious symptoms from electromagnetic exposure. However, everyone may affected without being aware of it, e.g. when using a mobile phone. According to the Royal Society for the Prevention of Accidents, you are four times more likely to have an accident if you use a mobile phone while driving. This is not due to holding the phone since using a hands-free type makes no difference. It is also not due to the distraction of holding a conversation, since talking to a passenger does not have the same effect. This leads us to the conclusion that the electromagnetic radiation from the phone is the most likely culprit.

This fits with the notion that spurious action potentials triggered by electromagnetic radiation creates a sort of “mental fog” of false information that makes it harder for the brain to recognise weak but real stimuli. For example, a driver using a mobile phone may still see the road ahead using the strong images from the central part of the eye but may be less aware of weaker but still important images coming from the side. He may also be less able to conduct relatively complex tasks such as judging speed and distance in relation to other moving vehicles. This needs a lot of “computing power” and will therefore be more susceptible to random interference. Although an experienced driver may do much of his driving automatically, his brain still has to do just as much work as if he were still learning; it is just that he is unaware of it. Therefore, an old hand at driving is just as likely to be forced into making a mistake when using a mobile while driving as a novice, so don’t imagine you can get away with it just because you have been driving for years. Another important point is that, if this theory is correct, and the electromagnetic signal is mainly to blame, not only is it inadvisable to use a mobile yourself while driving, but your passengers should not use them either since their radiation may still affect *your own* driving.

The theory behind it all

We have seen that weak electromagnetic fields can remove calcium from cell membranes and make them leak. If we theorise about the mechanism, we can explain many of the seemingly weird characteristics of bioelectromagnetic responses. These include why weak fields can be more effective than strong ones, why low frequencies are more potent, why pulses do more damage than sine waves and what is special about 16Hz. The following hypothesis was proposed by Goldsworthy (2006).

The role of eddy currents

Before they can give biological effects, the electromagnetic fields must generate electrical "eddy currents" flowing in and around the cells or tissues. Both the electrical and magnetic components of the fields can induce them and they tend to follow low impedance pathways. These can be quite extensive; for example in the human body, the blood system forms an excellent low resistance pathway for DC and low frequency AC. It is an all-pervading system of tubes filled with a highly conductive salty fluid. Even ordinary tissues carry signals well *at high frequencies* since they cross membranes easily via their capacitance. In effect, the whole body can act as an efficient antenna to pick up electromagnetic radiation. If you need convincing, try a simple experiment. Tune in a portable radio to a weak station and see by how much you can improve reception by simply grasping the antenna. There is little doubt that signals transmitted by a mobile phone, even if it is a hands-free type, will reach all parts of the body, including the sex organs.

How calcium is released

The membrane: - Most biological membranes are negatively charged, which makes them attract and adsorb positive ions. However, these ions are not stuck permanently to the membrane but are in dynamic equilibrium with the free ions in the environment. The relative amounts of each kind of ion attached at any one time depends mainly on its availability in the surroundings, the number of positive charges it carries and its chemical affinity for the membrane. Calcium normally predominates since it has a double positive charge that binds it firmly to the negative membrane. Potassium is also important since, despite having only one charge, its sheer abundance ensures it a good representation (potassium is by far the most abundant positive ion in virtually all living cells and outnumbers calcium by about ten thousand to one in the cytosol).

The signal: - When an alternating electrical field from an eddy current hits a membrane, it will tug the bound positive ions away during the negative half-cycle and drive them back in the positive half-cycle. If the field is weak, strongly charged ions (such as calcium with its double charge) will be preferentially dislodged. Potassium (which has only one charge) will be less attracted by the field and mostly stay in position. Also, the less affected free potassium will tend to replace the lost calcium. In this way, weak fields increase the proportion of potassium ions bound to the membrane, and release the surplus calcium into the surroundings.

Why there are amplitude windows

The main effect, electromagnetic treatment is to change the normal chemical equilibrium between bound calcium and potassium in favour of potassium. Even very weak fields should have at least some effect. This effect should increase with increasing field-strength, but only up to a point. If the field were strong enough to dislodge large quantities of potassium too, there will be less discrimination in favour of calcium. This gives an *amplitude window* for the *selective* release of calcium, above and below which there is little or no observable effect.

The field strength corresponding to the amplitude window may vary with the ease with which eddy currents are induced and the nature and physiological condition of the tissue. There may also be more than one in any given tissue. Blackman et al. (1982) discovered at least two for brain slices, perhaps because the brain contains two main types of cell; the neurones and the glial cells, each of which have different membrane compositions.

Why low frequencies and pulses work better

The hypothesis also explains why only frequencies from the low end of the spectrum give biological effects and why pulses and square waves are more effective than sine waves. Only if the frequency is low will the calcium ions have time to be pulled clear of the membrane and replaced by potassium ions before the field reverses and drives them back. Pulses and square waves work best because they give very rapid changes in voltage that catapult the calcium ions well away from the membrane and then allow more time for potassium to fill the vacated sites. Sine waves are smoother, spend less time at maximum voltage, and so allow less time for ion exchange.

Frequency windows

The hypothesis also explains the curiosity that some frequencies are especially effective, with 16Hz being the most obvious. This is because 16Hz is the ion cyclotron resonance frequency for potassium in the Earth's magnetic field. (See Box). When exposed to an electromagnetic field at this frequency, potassium ions resonate, absorb the field's energy and convert it to energy of motion. This increases their ability to replace calcium on cell membranes. Although the extra energy gained by each potassium ion may be small, the fact that there are about ten thousand of them competing with just one calcium ion for each place on the membrane means that even a slight increase in their energies due to resonance will have a significant effect.

Amplitude modulated and pulsed radio waves also work

Amplitude modulated and pulsed radio waves consist of a high frequency "carrier" wave whose strength rises and falls in time with a lower frequency signal. This is the basis of AM radio transmissions, where the low frequency signal comes from an audio source. The receiver demodulates the signal to regenerate the audio. Unmodulated carrier waves usually have little or no biological effect, but if modulated at a biologically-active low frequency (such as 16Hz) they give marked effects (Bawin et al. 1975). This has posed problems for scientists trying to work out how living cells could demodulate radio signals to regenerate the low frequency and elicit a biological response.

However, we can now explain it easily. Imagine a child bouncing a ball continuously against the ground. The harder he hits it, the higher it bounces and the greater its average height. The layer of free positive ions that congregate near but are not bound to the negatively charged surface of a cell membrane will behave in the same way. They bounce against the membrane in time with the radio wave, and the average distance of the electrical centre of the layer from the membrane rises and falls with any amplitude modulation. Modulating the signal at 16Hz makes the centre of the layer rise and fall at 16Hz. It does not have to move very far since any free potassium ions in the vicinity will resonate, gradually gain energy from the oscillations and become more able to bombard and displace calcium ions bound to the membrane.

How calcium loss makes holes in membranes

Cell membranes are made of sheets of fatty materials called phospholipids surrounding islands of protein. The proteins have a variety of metabolic functions, but the main role of the phospholipids is to fill the spaces between them and act as a barrier to prevent leakage. Calcium loss weakens the phospholipid sheet and makes it more likely to leak; but how does it do this?

The membrane phospholipids are long molecules. One end consists of hydrophobic (water hating) hydrocarbon chains. The other end has a negatively charged phosphate group and is hydrophilic (water loving). In a watery medium, they arrange themselves spontaneously to form double-layered membranes with a central core made from their water hating ends. Their water loving phosphate ends face outwards towards the water. The affinity that the central hydrophobic parts have for one another helps hold the membrane together but the negatively charged phosphate groups on the outside repel each other and try to tear it apart. Normally, the membrane is stabilised by positive ions that fit in between the negative phosphate groups, so that they do not repel each other. They act as a kind of cement that helps to hold the membrane together.

However, not all positive ions stabilise the membrane equally well. Calcium ions are particularly good because of their double positive charge, but monovalent potassium, with just one charge, is only mediocre. Therefore, when electromagnetic fields swap membrane-bound calcium for potassium, it weakens the membrane (These membranes are only a hundred thousandth of a millimetre thick) and it becomes more prone to accidental tearing and the formation of transient pores. This happens to some degree all the time, even in stationary artificial membranes (Melikov et al 2001), but the membranes of living cells are often stressed by the cells' moving contents, so the effects should be much greater. Fortunately, these pores are usually self-healing and the damage to the membrane is not permanent. However, during electromagnetic exposure there will be more tears, slower repair and consequently more overall leakage. The metabolic effects of even a brief period of leakage may be much longer lasting (e.g. if dormant genes are activated) and perhaps (as in the case of DNA damage) permanent.

Defence mechanisms

Calcium pumps: - Cells have to be able to pump out any extra calcium that has entered their cytosols to reset the low cytosolic calcium level every time it is disturbed by a programmed calcium influx. They should therefore be able to respond to unprogrammed calcium influx due to electromagnetic exposure. This should minimise any unwanted metabolic effects, but the scope to do this is limited. If it were too effective, it would also prevent legitimate cell signalling.

Gap junction closure: - If calcium extrusion fails and there is a large rise in internal calcium, it triggers the isolation of the cell concerned by the closure of its gap junctions (tiny strands of cytoplasm that normally connect adjacent cells) (Alberts et al. 2002). This also limits the flow of eddy currents through the tissue and so reduces the effects of radiation.

Heat shock proteins: - These were first discovered after exposing cells to heat, but they are also produced in response to a wide variety of other stresses, including weak electromagnetic fields. They are normally produced within minutes of the onset of the stress and combine with the cell's enzymes to protect them from damage and shut down non-essential metabolism (the equivalent of running a computer in "safe mode"). When the production of heat shock proteins is triggered electromagnetically it needs 100 million million times less energy than when triggered by heat, so the effect is truly non thermal (Blank & Goodman 2000). Their production in response to electromagnetic fields is activated by special base sequences (the nCTCTn motif) in the DNA of their genes. When exposed to electromagnetic fields, they initiate the gene's transcription to form RNA, which is the first stage in the synthesis of the protein (Lin et al. 2001).

As we can see, there are several defence mechanisms against damage by electromagnetic fields and there may be more we do not know about. They probably evolved in response to natural electromagnetic fields such as those generated by thunderstorms but are now having their work cut out to respond to the continuous and all-pervading fields associated with modern living. How well they perform will depend on many factors, including environmental conditions, the physiological condition of the cells and how much energy they have to spare. Consequently, they do not always succeed. When the defences fail, we may get visible symptoms from the radiation, but when they succeed, there may be little obvious effect.

The power and mobile phone companies have seized upon this characteristic variability to discredit work on the non-thermal effects of electromagnetic fields as being due to the experimental error. Nothing could be further from the truth. Many of these experiments are highly reproducible, especially the fundamental and all-important ones on the effects of the radiation on the release of calcium from cell membranes. Secondary effects further down the line may be less reproducible since they are more likely to be mitigated by the intervention of cellular defence mechanisms. Therefore, we cannot expect rigidly reproducible results in all circumstances any more than we can expect everyone to experience exactly the same side effects from taking a medicinal drug. However, that does not mean that they can be safely ignored!

Conclusion

In the latter part of this article, I have explained how weak electromagnetic fields can interact with cell membranes to weaken them and make them more permeable. As with all theories, it will be subject to modification and refinement as time goes by, but some facts are already inescapable. There is undeniable experimental proof that weak electromagnetic fields can remove bound calcium ions from cell membranes. There is also no doubt that bound calcium ions are essential for the stability of these membranes. Consequently, their loss will increase temporary pore formation under the mechanical stresses from pressure differences within the cell and abrasion by its moving contents. This very simple conclusion can account for virtually all of the known biological effects of electromagnetic fields, including changes in metabolism, the promotion of cancer, genetic damage, loss of fertility, deleterious effects on brain function and the unpleasant symptoms experienced by electrosensitive individuals. However, it seems possible that at least some cases electrosensitivity could be due to low levels of ionised calcium in the blood exacerbating the electromagnetic effects. If so, it may be possible to relieve some or all of the symptoms by conventional treatment for hypocalcemia.

Box

Ion Cyclotron Resonance

Abraham Liboff, in the mid 1980s, developed the idea that the frequency windows for the biological effects of electromagnetic fields were in some way due to ion cyclotron resonance, but he didn’t link it to membrane stability (Liboff et al.1990). Ion cyclotron resonance occurs when ions move in a steady magnetic field such as that of the Earth. The field deflects them sideways and they go into orbit around its lines of force at a characteristic “resonant” frequency, which depends on the charge/mass ratio of the ion and the strength of the steady field. Exposing them to an oscillating electric or a magnetic field at their resonant frequency lets them absorb its energy and they gradually increase the size of their orbits and their energy of motion. The resonant frequency for potassium in the Earth’s magnetic field is close to 16Hz. According to my hypothesis, electromagnetic fields at this frequency specifically increase the ability of potassium ions to bombard cell membranes and replace bound calcium. This increases the biological hazards of electromagnetic exposure near 16Hz and has already caused concern about the safety of the TETRA mobile telecommunications system, which transmits pulses at 17.6Hz.

Footnote

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References

Adey WR (1990) Electromagnetic fields, cell membrane amplification, and cancer promotion. In: Wilson BW, Stevens RG, Anderson LE (eds) Extremely Low Frequency Electromagnetic Fields: the Question of Cancer. Battelle Press, Columbus, Ohio, pp 211-249

Alberts et al. (2002) Molecular Biology of the Cell. (Garland Science, New York)

Bawin SM, Kaczmarek KL, Adey WR (1975) Effects of modulated VHF fields on the central nervous system. Ann. N.Y. Acad Sci 247: 74-81

Bawin SM, Adey WR (1976) Sensitivity of calcium binding in cerebral tissue to weak environmental electric fields oscillating at low frequency. Proc Nat Acad Sci USA 73: 1999-2003

Blackman CF (1990) ELF effects on calcium homeostasis. In: Wilson BW, Stevens RG, Anderson LE (eds) Extremely Low Frequency Electromagnetic Fields: the Question of Cancer. Battelle Press, Columbus, Ohio, pp 189-208

Blackman CF, Benane SG, Kinney LS, House DE, Joines WT (1982) Effects of ELF fields on calcium-ion efflux from brain tissue in vitro. Radiat. Res. 92: 510-520

Blank M, Goodman R (2000) Stimulation of stress response by low frequency electromagnetic fields: possibility of direct interaction with DNA. IEEE Trans Plasma Sci 28: 168-172

Diem E, Schwarz C, Aldkofer F, Jahn O, Rudiger H (2005) Non-thermal DNA breakage by mobile phone radiation (1800 MHz) in human fibroblasts and in transformed GFSH-R17 rat granulosa cells in vitro. Mutation Research/Genetic Toxicology and Environmental Mutagenesis 583: 178-183

Goldsworthy A (2006) Effects of electrical and electromagnetic fields on plants and related topics. In: Volkov AG (ed) Plant Electrophysiology – Theory & Methods . Springer-Verlag Berlin Heidelberg 2006. Pp 247-267.

Ha B-Y (2001) Stabilization and destabilization of cell membranes by multivalent ions. Phys. Rev. E. 64: 051902 (5 pages)

Jokela K, Puranen L, Sihvonen A-P (2004) Assessment of the magnetic field exposure due to the battery current of digital mobile phones. Health Physics 86: 56-66.

Liboff AR, McLeod BR, Smith SD (1990) Ion cyclotron resonance effects of ELF fields in biological systems. In: Wilson BW, Stevens RG, Anderson LE (eds) Extremely Low Frequency Electromagnetic Fields: the Question of Cancer. Battelle Press, Columbus, Ohio, pp 251-289

Lin H, Blank M, Rossol-Haseroth K, Goodman R (2001) Regulating genes with electromagnetic response elements. J Cellular Biochem 81: 143-148

Matthews EK (1986) Calcium and membrane permeability. British Medical Bulletin 42: 391-397

McLeod BR, Smith SD, Liboff AR (1987) Potassium and calcium cyclotron resonance curves and harmonics in diatoms (A. coffeaeformis). J Bioelectr 6: 153-168

Mehedintu M, Berg H (1997) Proliferation response of yeast *Saccharomyces cerevisiae* on electromagnetic field parameters. Bioelectrochem Bioenerg 43: 67-70

Melikov KC, Frolov VA, Shcherbakov A, Samsonov AV, Chizmadzhev YA, Chernomordik LV (2001) Voltage-induced nonconductive pre-pores and metastable single pores in unmodified planar lipid bilayer. Biophys J 80: 1829-1836

Muraji M, Asai T, Wataru T (1998) Primary root growth rate of *Zea mays* seedlings grown in an alternating magnetic field of different frequencies. Bioelectrochem Bioenerg 44: 271-273

Panagopoulos DJ, Chavdoula ED, Nezis IP, Margaritis LH (2007) Cell death induced by GSM 900-MHz and DCS 1800-MHz mobile telephony radiation. Mutation Research 626: 69-78

Sage C, Johansson O, Sage SA (2007) Personal digital assistant (PDA) cell phone units produce elevated extremely low frequency electromagnetic field emissions. Bioelectromagnetics. DOI 10.1002/bem.20315 Published online in Wiley InterScience (www.interscience.wiley.com)

Smith SD. McLeod BR, Liboff AR (1993) Effects of SR tuning 60Hz magnetic fields on sprouting and early growth of *Raphanus sativus*. Bioelectrochem Bioenerg 32: 67-76

Stenz H-G, Wohlwend B, Weisenseel MH (1998) Weak AC electric fields promote root growth and ER abundance of root cap cells. Bioelectrochem Bioenerg 44: 261-269

Wilson BW, Stevens RG, Anderson LE eds (1990) Extremely low frequency electromagnetic fields: the question of cancer. Battelle Press, Columbus, Ohio

factsheet

High Voltage Direct Current Electricity – technical information

Electric power is normally generated, transmitted and distributed as alternating current (AC).

Introduction

High voltage direct current (HVDC) technology is one of the technical options National Grid can consider for the future development of the transmission system in Great Britain.

Although HVDC has some disadvantages, as its integration within an AC system has to be carefully considered and its cost can be higher than the equivalent AC solution, the advantages of HVDC transmission are principally the following:

- the ability to interconnect networks that are asynchronous or that operate at different frequencies
- the ability to transmit power over long distances without technical limitations
- the ability to control power flows on the HVDC connection for all system backgrounds
- the ability to transmit power in either direction as desired by the network operator
- in certain cases the ability to improve AC system stability.

This document provides a technical overview of HVDC technology and the situations in which it is applied as an alternative to alternating current (AC) transmission. It describes the various types of HVDC technology and the components that make up a HVDC connection. It also considers operation and maintenance issues and the costs associated with HVDC transmission.

National Grid owns the high voltage electricity transmission system in England and Wales and operates the system throughout Great Britain at 275,000 and 400,000 volts (275kV and 400kV). The National Grid system is made up of approximately 7,200 kilometres (4,470 miles) of overhead line, 1,400 kilometres (870 miles) of underground cable and around 330 substations.

National Grid has a statutory obligation under the Electricity Act 1989 to develop and maintain an efficient, coordinated and economical system of electricity transmission, and to facilitate competition in the supply and generation of electricity. National Grid also has a statutory obligation to have regard to the preservation of amenity in developing the transmission system.

Electric power is normally generated, transmitted and distributed as alternating current (AC). AC power is well suited to efficient transmission and distribution, as the voltage can be increased or reduced by transformers. HVDC transmission of electricity offers some advantages over conventional AC transmission that leads to its selection in particular applications.

A typical application of HVDC is to transmit power between two independent AC networks that are not synchronised. Examples of this are the 2,000MW England–France interconnector linking the British and French transmission systems and the 1,000MW BritNed interconnector between Britain and The Netherlands.

Unlike AC, there is no technical limit on the length of cable or overhead line that can be used in HVDC connections, so HVDC has advantages for long transmission distances.

HVDC – how it works

A typical HVDC system is shown in simplified form in Figure 1. A converter at the sending terminal acts as a rectifier and converts the AC power into DC. A converter at the receiving terminal acts as an inverter and converts the DC power into AC. The connection between the converters may be by overhead line, cable, or both.

Power electronic valves (essentially high powered, electronic switches) within the converters allow the power flow to be controlled. The HVDC system is usually designed so that the converter at either terminal can be operated as either a rectifier or inverter and so the direction of the power flow can be reversed as required.

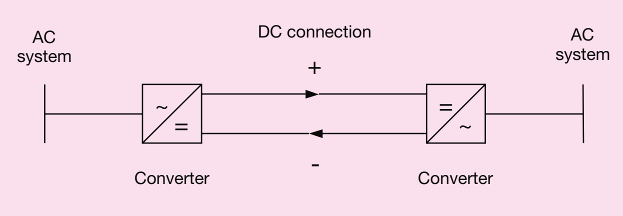

Figure 1: HVDC system

Two main converter technologies have been developed, current source converter (CSC) and voltage source converter (VSC).

HVDC converter technologies

Current source converters

Current source converters have been in commercial use since the 1950s. Most HVDC systems now in service are of the CSC type and the technology is well established. A typical current source converter (CSC) electrical diagram is shown below in Figure 2.

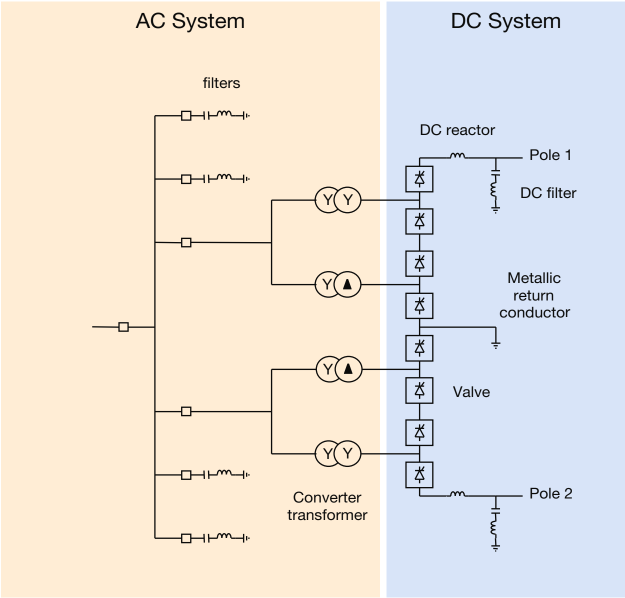

Figure 2: Example current source converter (CSC)

As a consequence of the AC-DC conversion technique utilised in CSC technology, the converter absorbs reactive power from the surrounding AC network and generates harmonic currents, both of which impact on the quality of electrical power. AC harmonic filters and reactive compensation must therefore be provided to maintain the quality of the electrical power. A further consequence is that the converter is dependent on the AC system voltage for its correct operation.

The current flow in the DC circuit is unidirectional. In order to reverse the power flow on a CSC HVDC connection, it is necessary to reverse the polarity of the DC voltage. This is performed by the DC converter control system.

AC harmonic filters are used both to limit AC harmonic currents and to compensate the reactive power absorption of the converter. The filters are switched in and out automatically as required to meet harmonic and reactive power performance limits.

Unlike AC, there is no technical limit on the length of cable or overhead line that can be used in HVDC connections, so HVDC has advantages for long transmission distances.

On the DC side of the converter, a reactor is provided to smooth the DC current. The reactor also reduces the peak current in the event of a fault on the DC connection. DC filters may also be required to reduce harmonic voltages on the DC circuit, particularly when the circuit includes overhead lines.

CSC HVDC systems are suitable for operation at high voltages and power transfers. A 6,400MW connection between Xiangjiaba and Shanghai in China, operating at +/- 800kV, went into service in 2010. This connection is made via DC overhead lines which are capable of carrying these high voltage DC currents. Power capabilities via DC cables are presently still limited to lower voltages and power transfer capabilities.

Voltage source converters

Voltage source converters (VSC) have been used in HVDC transmission systems since 1997. Comparatively few VSC HVDC systems are in service and the technology is still developing in terms of rating and capability. A typical voltage source converter is shown in Figure 3.

VSC converters use insulated gate bipolar transistor (IGBT) valves. The device is self commutating, meaning that the converter is not dependent on the AC system voltage for its correct operation.

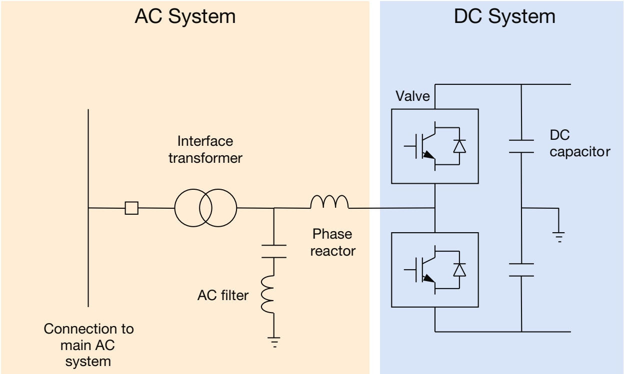

Figure 3: Example voltage source converter (VSC)

The VSC HVDC systems in service so far have been limited to lower voltages and power ratings than CSC systems. The 500MW East-West interconnector between Ireland and Great Britain, operating at +/- 200kV, represented the highest power rating for a VSC HVDC system when it went into service in 2012.

Comparison of CSC and VSC

The features of current source and voltage source converters are compared in Table 1.

	Current source converter	Voltage source converter
Maturity of technology	Mature	Developing
Valves	Thyristor, dependent on AC system voltage for commutation	IGBT, self commutating
Commutation failure	Can occur	Does not occur
Minimum DC power	Typically 5–10% of rated power	No minimum value
Reactive power exchange with AC system	50% of active power transmitted	Independent control of active and reactive power
Reactive compensation	Required	Not required
AC harmonic filters	Switchable filters required	Less filtering required, filters need not be switchable
Converter transformers	Special design required	Conventional transformers can be used
Reversal of power flow	DC voltage polarity reversal required	Controllable in both directions, no reversal of DC voltage polarity required
Converter station footprint (relative size)	200m x 120m x 22m (100%)	120m x 60m x 22m (~40%)
Conversion losses (per converter end)	0.7% to 0.8% of transmitted power	1% of transmitted power
DC voltage	Up to 800kV available	Up to 350kV available

Table 1: Comparison between current source converter and voltage source converter technology

HVDC transmission technologies

Cable types

There are two main types of cable technology suitable for use in HVDC applications, crosslinked polyethylene (XLPE) and mass impregnated (MI) insulation (see Figures 4 and 5). All cables consist of a copper or aluminium conductor surrounded by a layer of insulation (the thickness of which is dependent upon the operational voltage), a metallic sheath to protect the cable and prevent moisture ingress and a plastic outer coating. An additional requirement for cables intended for subsea use is steel armouring, which consists of steel wires helically wound around the cable, increasing the cable's strength and protecting it from the rigours of subsea installation.

Figure 4: MI cable

Figure 5: XLPE cable.

Source: Prysmian Cables & Systems Ltd

XLPE insulation is made by extruding the polymer over the cable core, and is the technology now generally used for AC transmission cables. XLPE cables are available for HVDC voltages up to 320kV, this could however increase in the future due to advancements in technology. XLPE cables are unsuitable for use in CSC applications where, in order to reverse the direction of power flow, the polarity must be reversed.

MI insulation is made by winding kraft paper around the conductor until the required insulation thickness is achieved. The cable is then placed in a vacuum chamber and heated to remove any air and moisture. A viscous oil is introduced which impregnates the paper, increasing the electrical strength of the insulation. A recent development uses polypropylene laminated papers, where thin layers of plastic are laminated to the paper layers, allowing the cable to operate at higher temperatures and therefore higher current ratings. HVDC, MI cables are presently available for voltages up to 600kV.

Cable installations

Generally, at least two cables are required for HVDC underground/subsea transmission, unless an earth/sea electrode is to be used at the converter stations, although it should be recognised there can be environmental issues with such a solution.

In a monopolar scheme, these will consist of a heavily insulated HV cable and a lightly insulated return cable; whereas in bipolar designs both cables operate at high voltages and require heavy insulation.

Because of the reduced power capacity of cables when compared to overhead lines, between four and six cables are required to match the capacity of an equivalent AC or DC overhead line. Existing cable technology limits continuous power transfer on a single cable DC bipole circuit to approximately 2GW, whereas a double circuit AC overhead line may transmit over 6GW.

Onshore

The same principles and installation techniques for onshore underground AC cables apply to DC, with the exception that reactive compensation is not required for DC transmission and fewer cables are usually needed (minimum of two cables for DC rather than three for AC).

Offshore cable installation, for both AC and HVDC, requires the use of specially designed cable-laying ships or barges.

As cables need to be spaced far apart to allow the heat generated to dissipate in the ground, a cable easement corridor of around 12m wide will be required for an HVDC route consisting of four cables, with increased width to account for section joints and access during construction and maintenance (see Figure 6). This causes a significant environmental impact in construction and reinstatement and results in ‘land sterilisation’, as the cable corridor cannot be used for construction or certain types of agriculture.

Offshore

In many cases, offshore transmission is better suited to HVDC applications than traditional AC. Using AC, offshore cable voltages are limited to 220kV, limiting power transfer capabilities unless many cables are used. Also, lengths of AC cable are very difficult (and consequently expensive) to joint offshore and reactive compensation cannot be installed mid-route, so transmission distances are restricted.

Offshore cable installation, for both AC and HVDC, requires the use of specially designed cable-laying ships or barges. To protect the cables from anchor strikes, they are preferably buried in the sea bed. Specialist, remotely operated submersible units are needed to cut the trench and install the cables.

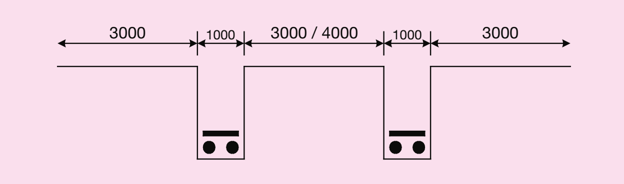

Figure 6: Example cable easement corridor (2 cables/pole)

Figure 7: BritNed CSC converter station

Where there is a requirement for the cables to cross existing subsea equipment such as pipelines, the cables can be protected, for example, by using concrete ‘mattresses’. For longer lengths of submarine cable, lengths of cable need to be jointed together on the ship while at sea. This is a very complex and time-consuming operation, needing highly skilled personnel and a spell of good weather of roughly three days to allow the laying ship to remain stationary while the cable is jointed.

Overhead lines

Overhead lines rely on the air gap between the conductors and the ground as electrical insulation and to provide cooling for the conductors. Conductors are suspended from towers by insulators made of either ceramics or polymers, although polymer insulators are generally used for HVDC applications because of their improved pollution performance (HVDC systems have a tendency to attract pollution/particulates).

HVDC overhead lines can be used up to 800kV and are capable of transporting more than 6GW on a single bipole route. However, transfers of this level have only been undertaken using CSC technology. As yet, VSC technology has not been proposed to power capabilities beyond 1–2GW.

HVDC converter station installations

Converter station current source converters

Figure 7 shows an example of a CSC converter station. Converter stations require a significant amount of land for their construction. CSC converter stations can vary in size due to the requirements of the station however an “average” size station will take up an area of land 200m x 120m, including indoor and outdoor equipment.

DC equipment attracts pollution/particulates from the atmosphere and so the valves and therefore DC switching arrangements, and often smoothing reactors, are housed in large climate controlled buildings nominally 22m high. The converter transformers are outdoors and can generate significant levels of audible noise.

The CSC converter’s requirement for harmonic filtering and reactive compensation make a significant contribution to the size of the converter station (which can be greater than 50% of the overall footprint).

Operational issues

Controllability

One of the key benefits of an HVDC system is the ability to precisely control power flows. In AC systems the power, like water, flows along the path of least resistance, which in some cases can result in unequal distribution of power across the transmission system. HVDC systems allow the operator to precisely control the flow across the circuit, which may help alleviate issues on the wider power system.

Impact of faults on the AC system

AC overhead line systems are very resilient under fault conditions. If an AC overhead line suffers a lightning strike then the power flowing in the network redistributes itself very quickly and without any need for external intervention.

Adjusting power flows on an HVDC link is not instantaneous and requires the intervention of the operator or control system. VSC-based systems are faster at responding to changes in system conditions than CSC-based systems, where polarity reversal must take place to change the direction of power flow.

An additional weakness, specific to CSC technology, is that faults on the AC system can introduce 'commutation failure' in the valves of the converter stations. As CSC converters take their voltage signal from the AC network, disturbances in this voltage, such as might be seen after a fault, can interrupt the power transfer. This may exacerbate the problems on the AC network.

HVDC system reliability

HVDC systems suffer all of the potential issues of AC technology but with additional failure modes introduced at the converter stations.

Overhead lines (OHL) generally experience more faults, such as lightning strikes, than buried transmission systems. A fault caused by lightning generally requires no repair as the air that breaks down for a flashover to occur self heals thus the fault is temporary. It is rare that equipment is damaged badly or needs replacing, but even if damage occurs maintenance is relatively easy on an OHL. Faults on cables on the other hand are permanent as damage occurs in the cable insulation and not the self healing air like on OHLs. Cable faults require extensive excavation to identify the location of the fault and repair it. This is worse for submarine cable systems, where repair means raising the cable from the sea bed, removing the damaged section and replacing it with a new section. A fault on a submarine cable is therefore very serious and can result in the HVDC system being out of service for up to six months.

Short-term overload

A useful characteristic of AC systems is their ability to withstand overloads for a short period of time. AC equipment can exceed its current rating for short periods before the conducting elements become too hot. This can allow the system operator valuable time to reconfigure the network and return power flows to normal levels.

However, in HVDC systems the valve elements heat up very quickly and cannot operate above their rating. This means that the capability of HVDC systems to deal with temporary overload conditions is limited unless the converter station has been designed with this in mind (at extra cost).

Multi-terminal operation

The AC transmission system is protected by high voltage circuit breakers which allow isolation of faulty sections of the network. The same is not true for HVDC systems because there are no commercially available HVDC circuit breakers at present.

Consequently, HVDC systems tend to be point-to-point systems and not interconnected, as any single fault would shut down the entire interconnected HVDC network.

Only a few of the HVDC links in service in the world are multi-terminal applications, each with much less operational flexibility than AC systems. The properties of VSC HVDC systems in theory lend themselves better to multi-terminal operation over CSC systems, although in comparison with CSC, experience with VSC multi-terminal HVDC links is very limited.

This limitation of HVDC systems is fundamental when considering the future expandability of a transmission network. It is a relatively simple matter to, for example, connect a new power station to the AC system, whereas to introduce extra infeeds or outfeeds into an HVDC system is not easily achieved.

Voltage source converters

The footprint of a VSC converter station is considerably smaller than that of a CSC station, as there is no need for reactive compensation equipment. As with CSC stations the footprint of VSC converter stations can vary but an average footprint could be 120m x 60m x 22m. All equipment is generally indoors with the exception of the connection to the AC grid.

To reduce the footprint further, the VSC converter can be constructed on two levels. VSC is the preferred technology for the connection of wind farms located far from the shore where the distance makes an AC connection uneconomic and unfeasible.

Economics

Capital costs

The capital costs of HVDC installations can be much higher than for equivalent overhead line transmission routes. It is very difficult to give a direct comparison, however, as the cost of any HVDC and AC project is dependent upon a multitude of project-specific factors such as technology used and route length. Under some circumstances, HVDC may be more economic than equivalent AC transmission; generally the longer the route length the more competitive HVDC becomes. The break-even distance will vary depending upon the installation type but can be over hundreds of kilometres.

Converter stations

DC converter stations represent a significant portion of the cost of any HVDC installation. AC harmonic filters and reactive compensation add to the cost of CSC stations but in comparison with VSC stations the costs are broadly similar. However VSC converters have presently only been installed at lower maximum ratings than CSC converters so, in terms of capital cost per unit of power, they have generally been more expensive.

Cables

When used in AC systems, long HVDC cable routes incur a high capital cost. However, DC cables normally:

- require two cables per circuit rather than three
- do not require reactive compensation mid-route
- are more highly rated than equivalent AC cables.

Overhead lines

As in AC networks, overhead lines are the most economic means of power transmission in HVDC systems.

Transmission losses

Converter stations

The process of converting AC power to DC is not 100% efficient. Power losses occur in all elements of the converter station: the valves, transformers, reactive compensation/filtering and auxiliary plant. CSC converter stations incur a loss of 0.7-0.8% per converter station (1-2% for a link including a converter station at each end). VSC converters suffer higher losses in the region of 1% per converter (2% per link).

As there is a cost associated with lost power, these losses can significantly increase the cost of a converter station over its lifetime. When compared to AC transmission, the converter station losses render HVDC transmission considerably less efficient than AC transmission over short distances.

Cables and overhead lines

Over short distances, the losses in both cables and overhead lines are very small. Losses in AC transmission are in the region of 0.7%–1% per 100km for an overhead line route and 0.3%–0.6% for a cable system. DC transmission losses are slightly less for a given power transfer. Consequently, very long lengths of cable or overhead line are required before the losses in the converter stations are offset and HVDC becomes more efficient than AC.

Maintenance

Another cost that must be considered when evaluating transmission projects is the cost to operate and maintain the equipment. Maintenance costs for DC systems are generally higher than AC because of the complex converter stations that require regular, specialist maintenance.

Refurbishment

AC transmission has an expected lifetime of approximately 60–80 years, with mid-life refurbishment of overhead lines, which are the largest capital component, needed after 40 years. In contrast, HVDC systems have a shorter life expectancy of 40 years, and large parts of the converter stations (valves and control systems) are likely to need replacing after 20 years.

Glossary & Abbreviations

Abbreviation	Meaning
AC	Alternating current
Bn	Billion
CSC	Current source converter
Converter	Part of an HVDC system which either converts AC electricity to DC or alternatively converts DC electricity to AC
Commutation	Part of the process of converting alternating current to/or from direct current
DC	Direct current
GW	Gigawatt (one thousand Megawatts)
HV	High voltage
Hz	Hertz
Inversion	The conversion of DC electricity to AC electricity (as performed by an inverter)
km	Kilometre
kV	Kilovolt (one thousand volts)
MI cable	Mass impregnated insulated cable
MW	Megawatt (one million watts or one thousand kilowatts)
Reactive power	A form of power which is required to maintain voltage on the transmission system
Rectification	The conversion of AC electricity to DC electricity (as performed by a rectifier)
VSC	Voltage source converter
XLPE cable	Cross-linked polyethylene insulated cable

Hornsea 3
Offshore Wind Farm

Ørsted

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14 February 2018

Letter regarding Hornsea 3 [Ref: ZA32533-JK]

Dear Mr Lamb,

Thank you for your letter on behalf of the Friends of North Norfolk. As requested, I have responded to each of the points raised in your letter and those within the attachments from William Horabin (Annex 1) and Ian Shepherd (Annex 2).

First and foremost, I would like to stress that we recognise that organisations such as the Friends of North Norfolk and other individuals with whom we have consulted, are generally supportive of renewables and offshore wind power and that their concerns relate to specific aspects of our proposal and not the technology in general. This is reflected in the views expressed at our consultation events, which are summarised in the various reports we have produced.

The 'Rochdale Envelope' approach is necessary for applications where the details of the whole project are not available when the application is submitted. This is particularly relevant for maturing industries such as offshore wind power, where the technology itself is constantly evolving. However, it should be noted that is not limited to offshore wind power or energy generation in general. This is emphasised in Advice Note Nine: Rochdale Envelope, produced by the Planning Inspectorate (available at https://infrastructure.planninginspectorate.gov.uk/legislation-and-advice/advice-notes/) from which William Horabin's note appears to have been generated.

As further detailed in the advice note, the Rochdale Envelope approach is identified in the Overarching National Policy Statement for Energy (NPS) (EN-1) and the NPS for Renewable Energy Infrastructure (EN-3). I have provided a high-level summary of how each of the points taken from the Planning Inspectorate Advice Note and raised within the note from Willian Horabin will be dealt with in the final application for Hornsea Project Three in Annex 1 to this letter. A point by point response to Ian Shepherd's letter is provided in Annex 2.

The technical requirements for use of either a High Voltage Alternating Current (HVAC) or High Voltage Direct Current (HVDC) transmission system have fed into the design parameters presented in the Preliminary Environmental Information Report (PEIR) which will be further refined for the final application Environmental Statement (ES). The likely effects of the proposed development will be assessed based on the 'worst-case' or 'maximum design' scenario in accordance with best practice. This assessment will inform any proposed mitigation measures and we as the developer, must be able to demonstrate that the proposed mitigation measures adequately minimise any potential significantly adverse effects.

In response to your question regarding the width of land required, HVDC cable circuits are typically able to transport more power than HVAC cable circuits. Therefore, if using HVDC it is possible we may be able to use a reduced number of electrical circuits (currently the maximum is six circuits) which could result in a narrower corridor being required of indicatively 60 metres (of which 20 metres is for temporary construction works only) rather than the 80 metres required for HVAC (of which 20 metres is for temporary construction works only). However, in accordance with the Rochdale Envelope approach, we will conduct our assessments based on a realistic worst-case scenario, which could be either HVAC or HVDC technology depending on the impact being assessed.

As you state in your letter, use of HVDC technology avoids the need for a booster station in North Norfolk. However, it is not necessarily the case that HVAC technology would always result in lower impacts. For example, using HVDC technology would likely require a larger onshore substation in South Norfolk to convert the electricity to AC before it reaches the grid. Therefore, in relation to the onshore substation, the HVDC option often generates the maximum design scenario and would not necessarily reduce impacts across the project.

Therefore, whilst HVAC may present the worst-case in terms of the width of the onshore cable route, HVDC may present the worst-case for other assessments. It is of note that the primary impacts associated with the onshore cable corridor will be seen during the construction phase. Once operational, farming will be able to continue over the cables, the project will ensure that agricultural land is restored to its previous state and will be required to restore any hedgerows that have had to have been removed. Comparatively, the impacts associated with the onshore substation will occur over a longer timeframe.

It is therefore relevant to note that the Environmental Impact Assessment (EIA) will look at the likely environmental effects along the entire route, taking account of the fact that different technologies could present the worst-case for different types of impact, in different areas or during different phases of the project (i.e. a construction impact or an operational impact). This will be considered throughout the final EIA and if significant adverse effects occur, appropriate mitigation will be considered and proposed by the project.

The proposed cable corridor routing, which we have now published, as well as Horizontal Directional Drilling (HDD) (regardless of whether the cables are HVDC or HVAC) at over 70 locations along the route, will minimise impacts associated with the installation and operation of cables. It was not possible before now to commit more specifically to the location of the HDDs sites as this could only be done as the route was refined. The final cable route as well as the location and number of HDDs proposed along the route has been driven by inputs from our stakeholders, including local communities so we believe that this will alleviate many of the concerns raised by the Friends of North Norfolk.

HVAC is the tried and tested transmission technology for offshore wind farms and one could argue that it would have been simpler to apply for only the one technology, however, the 'Rochdale Envelope' approach allows to us to consider different technological solutions. On other projects, this flexibility has enabled developers to utilise new technology that was not commercialised at the time of applying for consent that could be a better solution both environmentally and economically. For example, on our Burbo Bank Extension project we deployed the 8-megawatt turbines for the first time commercially. Increasing the scale of turbines not only reduces the area of seabed impacted by the project, but has also significantly contributed to the recent cost reductions witnessed across the offshore wind sector.

At present, all UK offshore wind farms use HVAC technology and the technology, it's capabilities and limitations are well understood. To date, HVDC has more commonly been used to transmit electricity from one grid to another in the form of an interconnector and has yet to be applied to any UK offshore wind farms. Although there is some experience using HVDC for offshore wind farms in Germany, the structure of the German market is quite different to the UK (in that offshore transmission connections are centrally planned and delivered by the onshore utility) and the use of DC technology for offshore wind farms is still maturing. The use of HVDC for offshore wind farms adds additional complexity in terms of greater infrastructure interfaces offshore and in some instances technical issues and delays have been experienced. Furthermore, due to the increased complexity of offshore HVDC systems and limited experience, transmission reliability is lower meaning that over time, less offshore wind energy can be transmitted to the grid.

Aside from the technology maturity, there are very few suppliers in the world with the capability of producing and supplying HVDC transmission technology (for the cables and convertor stations) that would be needed for a wind farm of this size, and delivery lead times can be considerably longer than for equivalent HVAC systems. In light of the above, there are risks associated with only taking the DC option forward at this time and as the developer, we are responsible for ensuring the proposed development is feasible and can be realised within a reasonable timeframe.

There is a certain level of confidence in the UK wind industry that HVDC technology <u>will become more mature</u> before Hornsea Project Three will connect, but there is currently **<u>no certainty and therefore no guarantees can be made.</u>** Therefore, committing to solely HVDC now could restrict or even prevent the development of the project in the future if we do not see the necessary developments in the market. We may well eventually choose to opt for HVDC transmission technology; however, it is considered that to only seek a consent (planning permission) for such a technology (and exclude HVAC) could affect the overall and eventual deliverability of the project.

Due to current uncertainty, a decision on which transmission system to adopt will not be made until post consent after extensive engagement with potential systems suppliers has taken place.

We have noted that North Norfolk have expressed a preference for the proposal to be taken forward using DC technology if feasible. We also understand that it is important for us as the developer to explain to consultees why it is not possible to finalise certain elements of the application. In this regard, we have recently updated our Frequently Asked Questions (FAQs) document on our website, which provides more information on the two technologies and explains why is not possible at this stage for the Project to commit solely to DC technology.

Through our consultation process we have sought to take into consideration the feedback received in response to the proposed onshore HVAC booster station (if required) and this is demonstrated through our site selection process. We recognise that for consultation to be effective there needs to be a genuine possibility to influence the proposal. Consideration has been given to areas of important landscape value. This has been informed by ongoing environmental and technical assessments, as well as feedback from statutory bodies, landowners and members of the local community.

Our final ES will present the key-project parameters for HVDC and HVAC scenarios (in Volume 1, Chapter 3 Project Description) in order to represent the Maximum Design Scenario for the specific assessments in the final EIA. This will build on the information presented in the Preliminary Environmental Information Report (PEIR) version of the chapter. In many cases, the maximum project parameters are the same for both technologies. As highlighted above, in relation to the width of the onshore cable corridor for HVAC and HVDC solutions, the HVAC solution will require a corridor width of 80m (of which 60m is permanent easement) whilst the HVDC solution could require an approximate corridor width of 60m (of which 40m is permanent easement). Using the Rochdale Envelope approach, we focus on the Maximum Design Scenario to ensure that mitigation measures adequately consider these, where appropriate. As outlined above, it is not possible to commit to HVDC technology at this point in time so to present an assessment on the basis of an HVDC onshore cable corridor would not present the Maximum Design Scenario for which we are seeking consent.

Hopefully the above helps to explain why is it essential for the Project to keep both options open and provides some reassurance in terms of how the potential impacts of both schemes are being captured as part of our environmental assessments.

Yours sincerely

Emily Woolfenden
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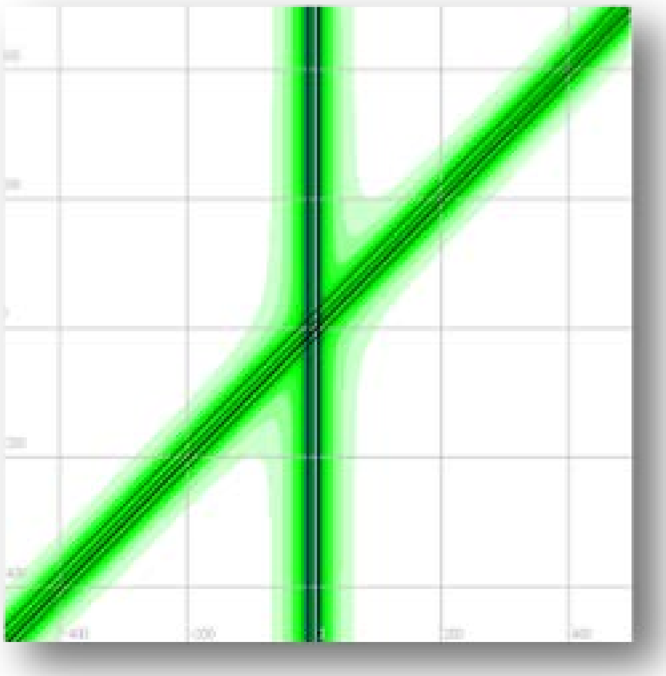
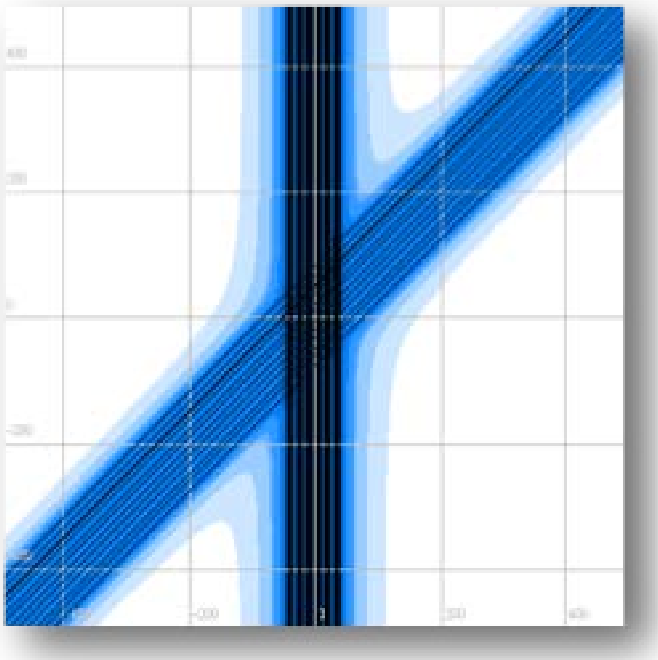
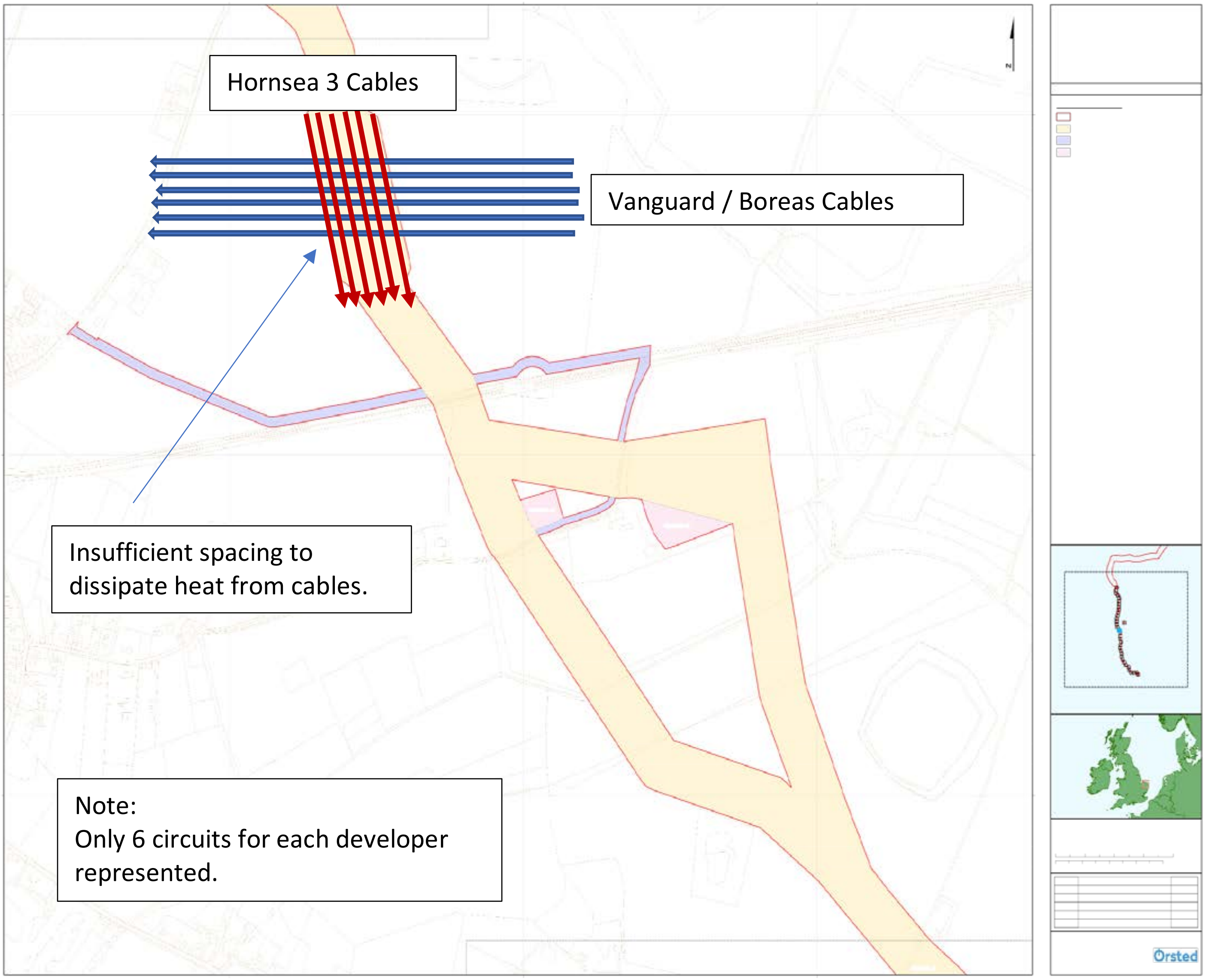
cc: Stuart Livesey (Project Development Manager)





Applicant states that the crossing is at 90 degrees.
Why have they carried out their calculations for a crossing of approximately 45 degrees?



Hornsea 3 Cables

Vanguard / Boreas Cables

Insufficient spacing to dissipate heat from cables.

Note:
Only 6 circuits for each developer represented.