16010859-ETD/POL 11-1387A

Study for the EirGrid East-West Interconnector high voltage DC 200 kV land cables

An independent assessment

Arnhem, June 29, 2011

Authors: Alex Hartsuiker and Frank de Wild

By order of EirGrid and Rush Community Council

author :	A. Hartsuiker/F.H. de Wild	2011-06-29	reviewed :	W. Boone	2011-06-29
35 pages			approved :	J. Offerman	2011-06-29

KEMA Nederland B.V. Utrechtseweg 310, 6812 AR Arnhem P.O. Box 9035, 6800 ET Arnhem The Netherlands
T +31 26 3 56 91 11 F +31 26 3 89 24 77 contact@kema.com www.kema.com Registered Arnhem 09080262

CONTENTS

1 INTRODUCTION

The Government of Ireland has decided that a strategic energy link, in the form of an electrical High Voltage Direct Current (HVDC) interconnector of 500 MW capacity should be developed between Ireland and Britain with ownership of the interconnector vested in EirGrid. The development of the interconnector is consistent with moves towards more European electricity interconnection between regional markets, as espoused by the European Commission. The East West Interconnector is identified as being of critical national strategic importance as part of the Irish Republic National Development Plan 2007 - 2013.

Currently the project is well on its way with approximately 60% of the interconnector constructed. The planned route of the interconnector has been established, and all necessary consents have been granted for installation and commissioning. The interconnector has its landfall on the North beach of Rush, a Town of roughly 8000 inhabitants, situated some 30 km North of Dublin City Centre. The cable route follows public highways from the beach through Rush town and onto the substation situated at Woodland.

Rush Community Council (RCC) has raised safety objections to the chosen route. Despite consents granted and safety precautions engineered into the project design by EirGrid, RCC is not persuaded that safety for the community is within reasonable and acceptable limits and maintains opposition to the chosen route. RCC is opposed to the cables' route bringing the cables in close proximity to people's homes. RCC argues that Rush is surrounded by areas that could have been utilised to take the cables away from people's homes.

In order to address concerns which RCC has voiced on behalf of the Rush community, EirGrid has agreed to commission an independent party, with proven expertise and authority on the safety of HVDC systems, to deliver a safety assessment on the EirGrid design and plans. RCC has proposed KEMA as a suitably qualified and experienced independent provider of this East-West interconnector safety study.

KEMA's objective is to assess five different safety aspects of the HVDC interconnector cable route between the landfall at Rush North beach and the rail crossing at Ballealy. The exact contents of the safety aspects assessed by KEMA have been agreed by both EirGrid and RCC.
This safety study is not for the purpose to intervene on behalf of or to be an expert witness to one party, but to ascertain the facts relating to the safety of laying the East-West interconnector in public roads and to evaluate the project compliance with the applicable international and Irish safety standards regarding the five different safety aspects agreed upon.

A site visit has been conducted to the town of Rush on the 26th and 27th of April 2011. The information gained during this site visit is integrated in this report.

This report will give the results and conclusions reached after KEMA's assessment of the five safety topics agreed upon. The report is organised in sections, each focusing on a certain safety aspect, and is ended with a concise set of conclusions.

2 TOPIC 1: THE CHANCES ON A CABLE OR JOINT FAILURE

2.1 Introduction

In this topic the chances on a cable or joint failure due to internal or external causes are evaluated. This discussion is based on international experience gathered recently by Cigré and the information provided in the project.

It is to be emphasized that there are fundamental differences between AC cables and HVDC cables, but that these differences are mainly in terms of electrical behavior. In terms of mechanical behavior as is relevant for a discussion on cable failure and protection, the HVDC cable in Rush is comparable to 132 kV and 150 kV AC cables. Experience with 132 kV and 150 kV AC cables is employed as they are of a comparable construction as the HVDC cable installed in Rush and they are widely installed in urban areas.

2.2 The failure rate according to international experience

EirGrid has installed the cables inside ducts embedded in a mix of concrete and sand. This is called cement bound mix, CBM, which is a mix that hardens with a sufficient concentration of cement. In the town of Rush, the cables are installed directly under the public road, with a depth varying around approximately 1 meter. In these situations, the cable trench is fully filled with CBM. In agricultural areas located between the town of Rush and the Ballealy railway crossing, the cables are buried at a depth of 1.5 meter and the ducts are surrounded with CBM (100 mm at the top and bottom, 75 mm at each side). In these locations, above the CBM the native soil is reinstalled. In all situations, the cable trenches are marked using heavy duty marker boards approximately 30 cm above the cables and marker tapes approximately 60 cm above the cable ducts.

Compared internationally, the way these cables are protected using ducts and CBM against third party damage is rather good. Many power cables, ranging up to 400 kV AC, are installed directly in native or backfilled soils, which are more easy to penetrate and remove, while ducted cables are not always surrounded by CBM, and if they are, not always the full trench is filled with CBM. The use of marker tapes and marker boards is more standard however. These experiences from KEMA are supported by the information collected in Cigré TB 398 (*"Third party damage to underground and submarine cables"*, December 2009), as can be verified in Table 1. Note that in Table 1 the failure rate does not depend on the type of backfill used. Use of CBM will decrease the failure rates as stated in Table 1 even further. Therefore, installation of the cables in CBM or covering the cables in CBM can be considered as an extra form of mechanical protection of an already good design.

The failure rate of power cables per installation type is reported in Table 1. There is a clear difference between direct burial and the duct + pipe installation type. The latter installation type covers both cables in ducts and cables in pipes, of which some clarifying pictures are given in Figure 1. There is a factor of ~10 reduction in the failure rate due to external causes, while there also is a factor of ~7 reduction in the failure rate due to internal causes compared to cables which are direct buried.

Table 1: The failure rate of power cables per type of installation. International experience gained with AC cables.

Voltage level	Average Yearly Fault rate per 100 km circuit beginning 2001 to end 2005	Direct Burial	Ducts + pipes	Tunnels	Others (Bridges, troughs, Air)
60 to 219 kV	km installed (Info B1.10 and B1.21)	11579	12758	1236	1357
	External - Other Physical External Parameters	0.054	0.003	0.000	0.015
	External - Third Party Mechanical	0.154	0.014	0.000	0.118
	External - Total	**0.207**	**0.017**	**0.000**	**0.133**
	Internal (cable only)	**0.081**	**0.011**	**0.049**	**0.000**
220 to 500 kV	km installed (Info B1.10 and B1.21)	1303	2725	1319	110
	External - Other Physical External Parameters	0.153	0.015	0.030	0.029
	External - Third Party Mechanical	0.292	0.022	0.000	0.044
	External - Total	**0.445**	**0.037**	**0.030**	**0.000**
	Internal (cable only)	**0.292**	**0.000**	**0.030**	**0.000**

Figure 1: Cables in pipes (left) and cables in ducts (right), which are pipes cast in concrete. The pictures are examples given in Cigré TB 398.

From Table 1, it could be deduced that the average yearly failure rate for a 200 kV cable is expected to be about 0.028. However, it must be reminded that the failure rate reported is valid for AC cables, not for DC cables. For DC extruded cables as used in the East-West interconnector, there is less statistical information available. The reason for this, is the limited service experience with HVDC extruded cables. However, a lot of service experience is present on 150 kV and 132 kV extruded cables, which have similar mechanical behavior and strength as the 200 kV cables that EirGrid are installing.

Although there is a lack of information regarding the HVDC service experience, KEMA has the opinion that there are currently no reasons to assume a much higher failure rate for HVDC extruded cables compared to HVAC extruded cables. The bulk of the materials used are similar in both technologies, the manufacturers are similar, and the long duration testing is similar. Therefore, HVAC failure statistics form a good basis to evaluate the failure rate of HVDC cables as long as there is a lack of service experience of HVDC extruded cables.

Regarding the service experience however, also the joints must be considered. Cigré TB 379 (*"Update of service experience of HV underground and submarine cable systems"*, April 2009), enables to do this, and to focus on AC extruded cables. Combining the failure rates given by Cigré with the route length and amount of joints in the town of Rush, provides the total failure rate of the HVDC cable in the town of Rush, see Table 2.

Table 2: Failure rates.

	Failure rate unit	XLPE cables (AC) 60-219 kV (CIGRÉ TB 379, Table 11)	Amount of cable and joints between beach and Ballealy railway crossing	Failure rate [fail./yr]
Cable Internal	[failures/yr.100cct.km]	0.027	5 km	0.00135
Cable External	[failures/yr.100cct.km]	0.057	5 km	0.00285[2]
Joint Internal	[failures/yr.100 comp]	0.005	12[1]	0.0006
Joint External	[failures/yr.100 comp]	0.002	12[1]	0.00024
TOTAL	[failures/yr]			<0.00504[2]

Notes:
- there are 6 joint positions, each with 2 joints. The first joint position is the joint at the beach, the last joint position is at Ballealy railway crossing
- the failure rate for external damage with the installation method used in Rush, will give rise to a failure rate significantly lower than reported here, see table 1 and text.

Table 2 shows the failure rate of the HVDC cable circuit to be significantly lower than 0.005 failures per year. The assumptions under this number are:

- the HVAC statistics provided by Cigré are representative
- HVDC extruded cables fail equal or less than HVAC extruded cables
- the factor ~10 difference between direct burial of power cables and ducted installation as reported by Cigré, see above.

KEMA's opinion is that these assumptions are realistic, and therefore supports a total failure rate of <0.005 to be representative for the chance on a cable fault inside the town of Rush.

2.3 Failure rate reduction measures

From experience, it is known that the failure rate per circuit can be strongly influenced by the degree of organization and level of technical skills and knowledge of the parties involved. In order to keep failure rates low, focus must be on the following main issues:

1 **Supervision of installation by experienced supervisors**
During installation in a lot of cases situations are encountered that do not represent the engineering situation. For example, available space can be too little, or old pipes or cables appear during excavation. These situations ask for decisions being made by the supervisor, which often has a tight schedule to keep. It is important for the overall quality and reliability of the cable circuit that the supervisor makes the right decision in unforeseen situations. It prevents that the circuit is installed differently than engineered, and thereby reduces the chance of failure due to internal causes. The supervisor is most likely to make the right decisions if he understands the consequences of his decisions and the relation to the engineering of the circuit. Ensuring this quality of supervision should be organized by the installing and the commissioning party. Furthermore, careful logging of the events will make sure a quality check of the installation by engineers involved can be performed as will be discussed under point 4.

2 **Installation of cable circuit by skilled professionals**
In line with the previous point is the actual work being carried out as important as supervision of the site for quality assurance. Cables can be damaged by wrong handling of shovels and knives. This is most important in jointing two pieces of cable where small particles might cause the circuit to fail.

3 Knowledge of the position of the cables
During installation it is very important to record the actual position and actual installation of the cable. Recording the installation will ensure that it is possible to check the circuit's desired properties like for example ampacity and reliability. Furthermore, knowledge of the position of the cables ensures that as-built maps can be drawn which are crucial for prevention of third party damage. These maps have to be made available to excavators and construction companies.

4 Information to excavators and construction companies on how to do when they prepare and carry out their excavation activities
Since cable failures are mainly caused by third party damage it is crucial that third parties are informed as much as possible. Generally the utilities are informed about excavation work being carried out and asked for as-built drawings. It is in the utilities interest to make the required information available to the excavating and construction companies and should therefore employ a detailed and up-to-date archive. All information should be accurate and available quickly. Excavators should be skilled and well informed on the cables' position. Furthermore, as will be discussed in the next section, the trench layout is such that presence of the cables will not go unnoticed because of signal tiles and CBM on top of the cables.

Points 3 and 4 are extensively covered in the information supplied by EirGrid by:
- the code of Practice between EirGrid and Fingal County Council
- the code of Practice For Avoiding Danger From Underground Services
- the guidelines for working on roads.

Furthermore, KEMA was supplied with as-built drawings of the cable circuit to date.

Points 1 and 2 and quality control on points 3 and 4 are not covered in the information supplied and KEMA was unable to assess these points in full detail. However, the impression KEMA experienced during the site visit was positive regarding points 1 and 2 above.

During the site visit, KEMA found no evidence that there is no focus on keeping the failure rate low.

2.4 Presence of other infrastructures

At certain locations the installed cable is installed at 300 mm from water mains which are in some cases broken. These water mains do not form a treat to the cable, nor is there an increased chance of water treeing.

2.5 Conclusions

The following conclusions have been reached regarding the chances on cable and joint failures in the HVDC cable circuit through the town of Rush:

- compared internationally, the way the HVDC cables in the town of Rush are protected against third party damage is rather good
- the failure rate of the total route of the HVDC cable circuit through the town of Rush is expected to be significantly lower than 0.005 failures per year.

During the site visit KEMA found no evidence for inaccurate or careless installation procedures resulting in failures or future failures. Therefore, KEMA assumes that installation, installation supervision, cable location recordings, and information exchange to excavators carrying out works in the vicinity of the East-West interconnector is performed according to best practices. This has not been fully checked within the scope of this study.

3 TOPIC 2: THE CABLE TRENCH LAYOUT AND ITS MECHANICAL PROTECTION

3.1 Introduction

In this topic the cable trench layout and its mechanical protection is further evaluated. These are items of importance since they have a large influence on failures due to third party damage.

3.2 Cable trench layout

The cable trench layout used through the town of Rush shows that there are five main precautions being taken in order to prevent damage to the cable circuit from excavation work on top of the cable:

1. the cables are installed in ducts
2. the ducts are installed in CBM, see also section 2
3. the cables are installed typically at 1 meter depth (lowest depth: 0.9 m deeper depths present as well) in Rush, 1.5 m in agricultural areas
4. there are 10 mm thick Marker Boards approximately 0.3 m above the cables
5. there are warning tapes installed approximately 0.6 m above the cables.

Precautions in order prevent damage to the cable circuit from excavation work directly next to the cable consists of a layer of CBM and the cable duct.

The precautions taken are in line with the practices reported in Cigré TB 398 on third party damage. The use of CBM up to the top of the trench through the town of Rush can be seen as an additional measure to diminish accidental third party damage during the cable circuit's lifetime.

Cigré TB 398 indicates the following: "*Plastic or concrete cover plates protect against damage caused by hand tools and plants, and not against damage caused by digging machines. Cables in pipes, weak mix, troughs and cables installed in concrete encased duct banks offer increasing mechanical protection. But even these systems do not always offer sufficient protection from damage caused by heavy machinery*". With the CBM in place, the situation created in the town of Rush thus does prevent against a significant amount of third party damage, but not against all forms of third party damage.

Installation of the cables in ducts reduces the failure rate significantly as is shown in Table 1 / section 2. The main reason is the extra protection the ducts provide.

The depth of installation is especially important in agricultural areas where farmers work with heavy equipment that penetrates up to 0.5 m into the soil. This has been taken into account by burying the cable significantly deeper in these areas, and by not disturbing the top soil layers.

The marker boards act as mechanical protection as well as warning signal. They form a protection against excavation by third parties since these parties are warned when they reach the Marker Boards. The distance between the marker boards and the cable ducts is sufficient to prevent damage to the power cables.

The warning tape is a standard safety measure for underground installation and has proven to be useful. The distance to the surface of about 300 mm is sufficient.

In general KEMA's impression of the mechanical protection of the HVDC power cable circuit through the town of Rush is rather positive. Multiple measures have been taken to minimise the risk on mechanical damage. Compared to other cable circuits in Europe (e.g. 400 kV AC), for reference, this cable circuit is protected very well.

Within the cable route, the position of the duct for fibres is either in between the power cable ducts, or about 50 mm above these ducts as is shown in Figure 2.

Figure 2: Installation of DC cables.

In Figure 2 the distance between the warning tiles and the duct for fibres is about 80 mm. For the ducts in which the fibres are installed KEMA expects a little higher risk of third party damage, but given the tiles and the CBM this increase in risk is small. Furthermore, damage of the fibres does not form a safety hazard, and the position of the fibre ducts does not influence the safety of the DC cables. Increasing the number of fibres or increasing the traffic through the fibres will not influence the operation of the cable system.

In some locations along the cable route, trees are present. The installation of the cables in ducts with CBM on top and around it however prevents tree roots from damaging the cables to a significant extent. Roots tend to grow slowly and will have difficulty growing into CBM. For damaging a cable, first the roots must penetrate through the CBM and then damage a duct, which is possible, though unlikely to occur. Within the lifetime of the cable circuit, there will be a small chance on this type of failure, which is embedded in the failure rate due to external causes, reported in Table 1 and 2.

Observed deviation

An observed deviation considers the use of CBM below the ducts. Rush Community Council reported that this CBM below the ducts is missing in some places. To KEMA's opinion, this does however not form an increased safety risk. From a safety point of view, the CBM prevents direct excavation of the cables (from above or from the sides) to a certain extent, and the warning tapes and marker boards remind the excavating company that an important high voltage cable circuit is present. As excavation is performed either from the top or from the sides and not from below, and as in the case of horizontal directional drillings, there will be a certain spacing between the cable infrastructure and the crossing infrastructure, the missing CBM below the ducts will not lead to an increased safety risk.

3.3 Joint bay design

The joint bay design used in 6 locations in the town of Rush shows that there are 4 main precautions against external damage:

1 warning tape on top of the joint bay
2 stokbord marker tiles installed at about 0.75 m above the joint bay
3 precasted concrete slabs of 1.5 m x 1.0 m x 0.15 m thick 0.25 m above the joint bay
4 cables are installed at ~1 m depth.

Compared to the cable trench, the ducts around the power cables are removed in the joint section (with a length of about 14 m). This is common practice. As a backfill material also CBM is used as indicated by EirGrid. The major mechanical protection in place is formed by the precast concrete slabs present and the CBM. These slabs can not be removed or penetrated accidentally, and thus form a good protection against mechanical damage.

3.4 Quality assurance and quality control

All measures to prevent mechanical damage are according to European standard practice. Although there is hardly any experience with HVDC connections through densely populated areas there is a large experience with 132 kV and 150 kV AC cables through densely populated areas. Furthermore, in many cases cables are installed also close to peoples' homes as they are in Rush. The 132 kV and 150 kV AC cables carry comparable currents as planned for the HVDC connection through Rush. Based on experience with these cables we find that the cable through the town of Rush is protected very well compared to the average situation in Europe.

However, to benefit fully from the safety measures identified, quality control of the installation is required. Under time pressure it might be possible that the installation is not completely up to design standards. KEMA did not assess the quality of the installation performed and can therefore not assess the complete as built situation. However, the site visit conducted did not result in doubts regarding this issue.

3.5 Conclusions

In general KEMA's impression of the mechanical protection of the HVDC power cable circuit through the town of Rush is rather positive. Multiple measures have been taken to minimise the risk on mechanical damage. Compared to other cable circuits in Europe (e.g. 400 kV AC), for reference, this cable circuit is protected very well.

KEMA did not assess the quality of the installation performed and can therefore not assess the complete as built situation. However, the site visit conducted did not result in doubts regarding this issue.

4 TOPIC 3: EFFECTS OF A CABLE OR JOINT FAILURE

4.1 Introduction

Cable failures can be dangerous because of earth potential rise and because of the energy released during failure potentially causing soil uplifting together with fire and fumes. Earth potential rise might lead to electrical accidents like currents flowing through the body. The earth potential rise during a cable failure and its consequences will be discussed in section 5. In this section, the effects of the energy released during failure will be discussed.

There are two main physical processes that might lead to soil uplifting during a cable failure:

1 displacement of cables due to Lorentz force during short circuit
2 displacement of soil due to heat dissipation during short circuit.

These two causes will be discussed in the next sections, while in the third section a relation is made with the effect of similar failures on different cable circuits. In the fourth section this topic is concluded.

Effects of contact with the cable during short-circuit failure will be discussed in the next section topic were the Earth Potential Rise and Step- and Touch Voltages are discussed.

4.2 Lorentz forces

When the HVDC cables carry a current, Lorentz forces will act. The Lorentz force is proportional to the currents through the cables, but inversely proportional to the distance between them. The force acts perpendicular to the current direction and points away from the other cable in the situation of the East-West interconnector. This is schematically shown in Figure 3.

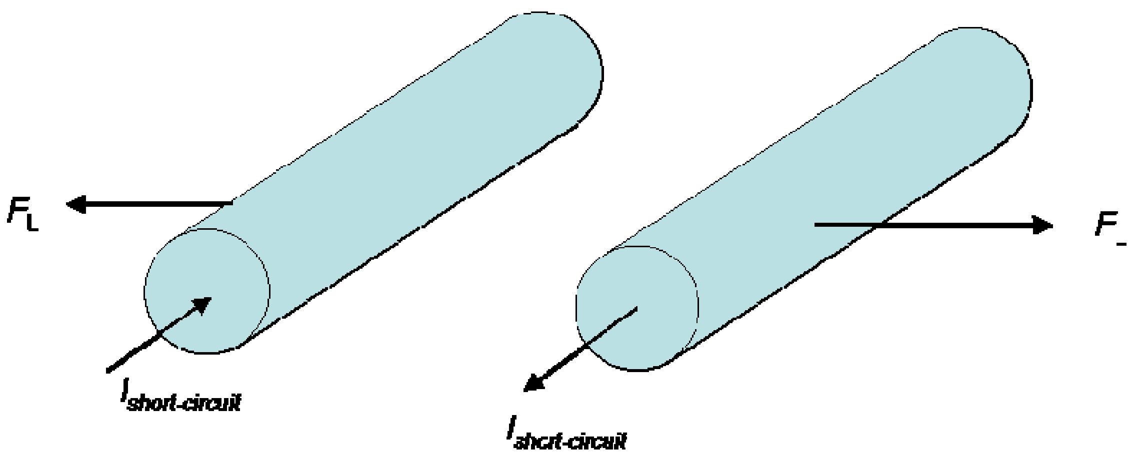

Figure 3: Lorentz forces F_L on parallel cables.

During a short circuit, wherever the short circuit location is, there will be a large current flowing through the power cables. In such short circuit situation, the East – West interconnector through the town of Rush will not cause any soil uplift, as the forces act horizontally rather than vertically (see Figure 3). Since the ducts are filled with grout no movement of the cable in the duct is expected.

4.3 Heat dissipation

When a cable or joint experiences a short circuit at a certain location, besides Lorentz forces in the complete cable circuit, there will also be heat dissipation on the location of the short circuit. This heat dissipation is caused by an arc between the conductor and the cable sheath, carrying the short circuit current. This arc leads to heat dissipation in the direct vicinity of the short circuit location, and thereby will lead to the quick expansion of local material. This quick expansion of material may lead to displacement and rupture of the soil above the cables. The material could then escape from the cable circuit together with hot fumes and some fire. The size of this effect depends on the amount of energy involved and the duration of the short-circuit situation. In cases of little energy dissipation the effects only take place within the cable and nothing is noticed outside the jacket of the cable. In cases of large energy dissipation there will be effects outside the jacket of the cable. In the following sections we will assess the amount of energy involved and the heat dissipated. We will relate these values to experiences in the field from recent projects in which KEMA was involved.

4.3.1 Energy dissipation

In the East-West interconnector, a cable failure will result in a short circuit current that is ~20 kA for about 1 ms due to the capacitive discharge of the power cable. After this, a short circuit current of ~2.5 kA flows for about 400 ms. During the short circuit, the voltage across the arc will be in the order of 50 V, as is know by KEMA’s high power testing laboratory by experience.

The current that flows through this arc generates heat with an efficiency of about 70%. Therefore, the heat power that is generated is in the order of 0.7 MW during 1 ms and 0.1 MW for 400 ms. In total, the dissipated energy is ~40 kJ.

This amount of energy will be related to other experiences with a similar energy release during a cable failure in section 4.4.

The energy dissipated will firstly heat up the grout filled ducts of the cables or the joint body depending on the location of the short circuit. If the dissipated amount of energy is significant, the duct itself and the surrounding CBM may be damaged on the place of the short circuit.

4.3.2 Temperature increase

A direct impression of the amount of energy dissipated during short circuit is obtained by calculating the temperature change of a certain mass of material. If a mass of soil is taken, the temperature change ΔT of this mass *m* by an amount of heat added *Q* can be found using the specific heat of soil, *c:*

$$\Delta T = \frac{Q}{cm}$$

Soil has a specific heat capacity of about 1.4 KJ/kg°C, from which the change in temperature of 1 kg of soil is 29 °C. 1 kg of soil corresponds to 0.4 liter of soil. Therefore, the amount of energy dissipated during a short circuit in the cable or a joint of the East-West interconnector, is equal to the amount of energy needed to increase the temperature of 1 kg of soil with 29 °C.

4.4 Field experience with short circuits

In order to relate the dissipated amount of energy of ~40 kJ (see section 4.3) to the effects to be expected, KEMA presents two cable failure situations which are very comparable regarding the amount of released energy. These are situations that have been encountered in projects that KEMA performed recently. The results that are shown in the next sections are not the results of experiments, but of actual installed systems.

Failure situation 1

Figure 4 shows the soil on top of a 1 m deep installed 132 kV AC cable after a short circuit current of 15 kA during about 50 ms. This equals an energy dissipation of ~38 kJ, almost equal to the energy dissipation in the East-West interconnector when a failure happens. After removing top layers, no disturbance of the soil is found (see Figure 4). The effects of the short circuit were only visible within centimeters from the cable system.

Figure 4: Soil in uncovered joint pit after a failure of 15 kA during about 50 ms.

Failure situation 2

Another experience relates to an HVDC cable, with similar transport power but a higher voltage as the East-West interconnector. The energy release during the failures is of the similar magnitude as the energy release which will be experienced in the East-West interconnector. Two failures have been assessed in this cable. In both cases the affected part of the cable was several meters in length, showing mainly cracks in the outer sheath, the jacket, and some marks of burning. In one of the cases the damage was only in the inner parts of the cable; the effects of the short circuit were not noticeable from the outside of the cable. It was clear that the damage was caused by heat dissipation and by arcing only, not leading to rupture of the soil above the cable, nor to escape of material, hot fumes and fire.

Based on the above experiences, KEMA expects that if a failure happens in the power cable, the effects of this failure will most likely be contained within the cable ducts, also in the case of partial exposure of the cable ducts. In the case of a failure at a joint location, KEMA expects that the effects of a failure are only noticeable in the first few cm around the joint and or cable.

4.5 Conclusions

The following conclusions have been reached:

- during a short circuit, there are Lorentz forces acting on the cables throughout the cable circuit. The cables will not move upwards or sidewards, and will stay inside the ducts
- at the location of a short circuit (cable or joint failure), the dissipated energy is ~40 kJ. This energy dissipation is relatively modest

- failures in other cable circuits with a very similar dissipated energy show almost no effects outside the power cable. It is therefore expected that only the power cable or joint and the first few cm of soil directly around the power cables (inside the ducts) may become affected at a possible failure location in the East-West interconnector. This will not affect any other infrastructure that is outside this zone of a few cm of soil.

5 TOPIC 4: EARTH POTENTIAL RISE AND STEP AND TOUCH VOLTAGES

5.1 Introduction

A short circuit in the power cable or joint of the East-West interconnector may also result in an 'earth potential rise', which is a localised rise of the electric potential. There are limits imposed on this earth potential rise due to safety considerations. When a person walks or touches objects above the power cable circuit, and if directly below his/hers feet there is a short circuit in the power cable circuit, this person must not experience a current through his/hers body above the governing safety guidelines. This effect is investigated in this section of the report.

On a transmission line connection, the earthing circuit comprises all earth electrodes and overhead or buried conductors making up the actual connection between the two substations. If a short circuit occurs in the cable, the short circuit current returns to the sourcing substations via the cable sheaths, other metallic return paths (such as earth wires) and the Earth itself. The part of the current returning to the source through the Earth (the soil) is responsible for the Earth Potential Rise (EPR)[1]. The EPR is the voltage rise of the earth during a fault condition. The EPR is calculated considering all possible earth fault current return paths, as normally only a small fraction of the total current returns to the sourcing substations via the soil.

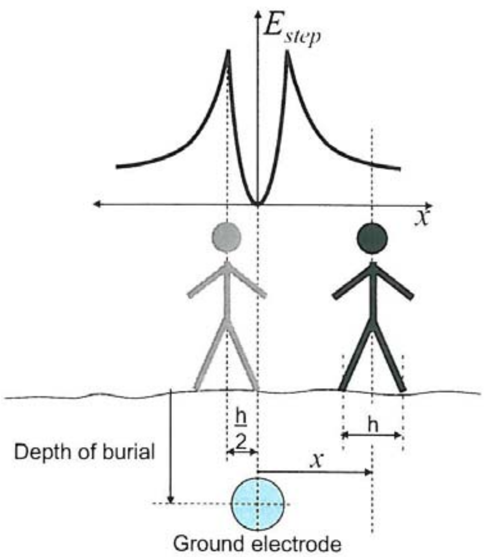

Figure 5: Step potential of a person approaching a buried electrode.

[1] In the US the earth potential rise is known as the ground potential rise (GPR)

The voltage of an earth electrode is imposed on the surrounding soil, establishing potential gradients in the soil with the highest potentials (and potential gradients) occurring in the direct vicinity of the short circuit. A person or animal standing or walking in this area, with his feet some distance apart, may be exposed to a so-called step voltage which is the difference in potential between the locations where the feet are placed. A typical step potential profile for a simple buried electrode is shown in Figure 5. In this figure, the separation of the person's feet is a distance "h" and his position relative to the centre of the electrode is "x". The highest step potential occurs when the person has a position so that one foot is directly above the electrode and the other is at distance "h", i.e. x=h/2. The step potential is also a function of the distance between the person's two feet. An increase in the distance "h" results in an increased step potential. However, a common approach taken for human beings is to standardize this distance at one meter.

The touch voltage is the voltage difference between hand and foot when a person is standing on the ground and touching a conducting object that is referred to a different voltage. Usually the voltage of the object being touched is assumed to be the Earth Potential Rise of the ground electrode (again, a grounding electrode may also give rise to an EPR, just as a short circuit location at which a current enters the soil). This situation is illustrated in Figure 6. The reach of a person is given by the distance, "h" in the figure. As for step voltages, this distance is standardized to one meter.

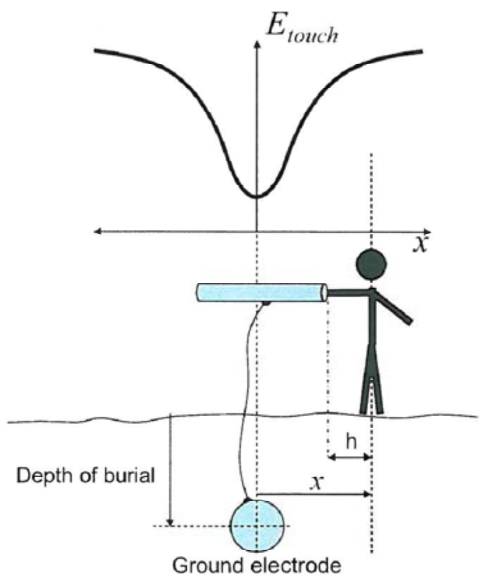

Figure 6: Touch potential of a person approaching a buried electrode.

The touch voltage increases as the person moves further away from the ground electrode location, approaching the Earth Potential Rise as the distance increases. However, the possibilities for a person to touch any conductive object, which is connected to the earthing grid, reduce as the distance between the person and the electrode increases.

To calculate the touch and step potential, various parameters like the maximum permissible current, the electrical resistance of the body and the soil and the current path through the body have to be taken into account. The maximum permissible touch and step potentials are given in the following standards: the NEN-EN 50522, IEEE 80-2000 and IEC 60479-1.

5.2 Earth potential rise

In case of the circuit under consideration the earth potential rise is 1350 V. This calculation result is valid under the following assumptions:

- an earth pen resistance of 30 Ω. The resistance of the earth pen is estimated by the manufacturer to be 30 Ω at a soil resistivity of 500 Ωm. Alternatively, at a soil resistivity of 200 Ωm the resistance of the earth pen is 12 Ω. We have assumed a worst case approximation using values of 500 Ωm and 30 Ω
- a short circuit current of 45 A through the soil. The manufacturer calculated that the short circuit current through the earth is only 1-3% of the total current during a short circuit. The maximum short circuit current has a duration of about 1 ms after which the current decreases in 400 ms from 10 A to 0 A.

5.3 Step and touch voltage

Based on the earth potential rise calculated, the step voltage may be calculated. However, as shown and discussed in section 5.1, this step voltage is always lower than the full earth potential rise of 1350 V. The maximum permissible step voltage is calculated to be 2800 V. This safety limitation on the step voltage is therefore always obeyed. Regarding the step voltage, the requirements given by the governing NEN-EN 50522, IEEE 80-2000 and IEC 60479-1 standards are met.

The maximum allowed touch voltage is calculated to be 1080 V. As this voltage is lower than the earth potential rise of 1350 V, the potential as a function of the distance from the point where the short circuit occurs is calculated. The result is shown in Figure 7.

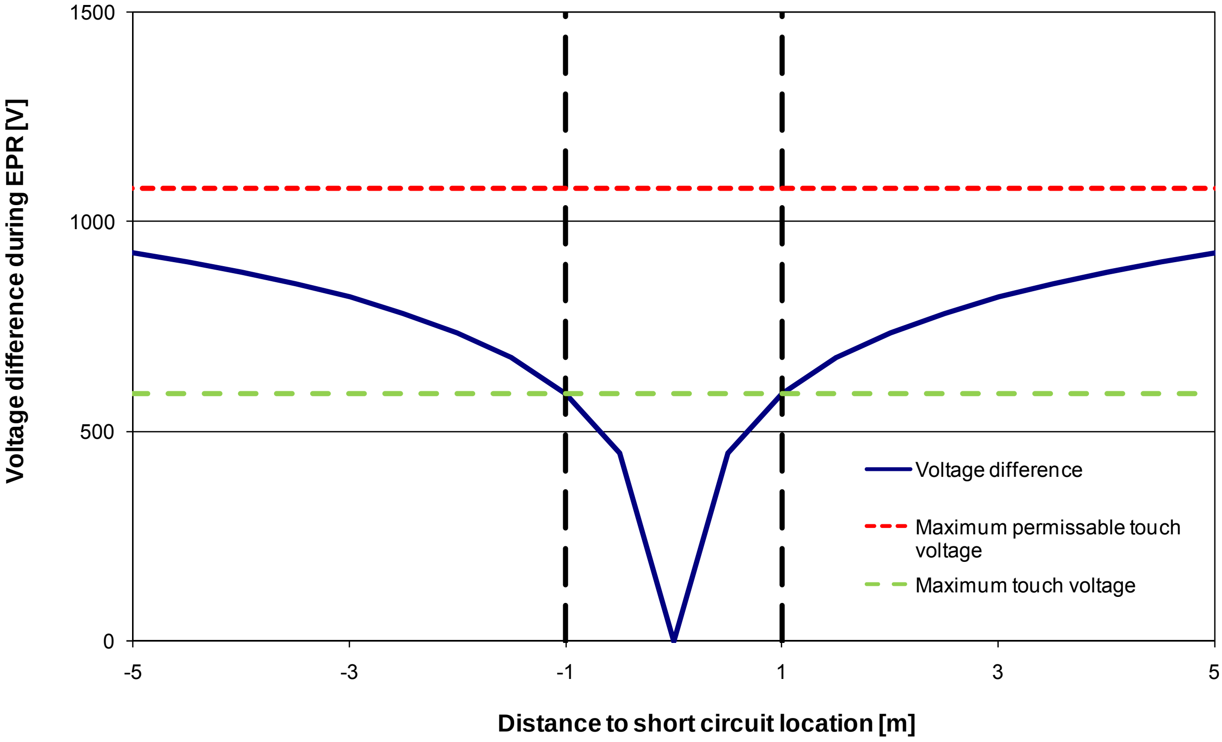

Figure 7: Touch voltage difference as a function of the distance to the location of the short circuit.

Figure 7 shows that the touch voltage, which is highest at 1 meter from the location of the short circuit (refer to section 5.1), is maximal 590 V. This touch voltage is lower than the maximum permissible touch voltage of 1080 V. Therefore, also the touch voltage meets the requirements stated in the governing NEN-EN 50522, IEEE 80-2000 and IEC 60479-1 standards.

Assumptions

The calculations of the step voltage and the touch voltage have been performed based on the standard IEC 60479-1, and the European standard NEN-EN 50522, which is compatible with the IEEE 80-2000 standard. Furthermore, next to the assumptions given in section 5.2, the following worst case assumptions were taken:

- the person wears no footwear (bare footed). Wearing shoes and other footwear increases the permissible touch voltage. In a city environment it may be likely that people wear no footwear near the circuit
- the calculations were performed for 50 Hz frequency. The standards are less strict for DC current since the DC-resistance of the body is higher.

5.4 Conclusions

The following conclusions have been reached regarding the earth potential rise, the step voltage and the touch voltage at the site of a possible short circuit failure of the power cable in the town of Rush:

- the Earth Potential Rise during a cable or joint failure (short circuit) is 1350 V
- regarding the step voltage, the requirements given by the governing NEN-EN 50522, IEEE 80-2000 and IEC 60479-1 standards are met. The step voltage is lower than 1350 V while the maximum permissible step voltage is 2800 V, both under worst case conditions
- regarding the touch voltage, also the touch voltage meets the requirements stated in the governing NEN-EN 50522, IEEE 80-2000 and IEC 60479-1 standards. The touch voltage is maximum 590 V while the maximum permissible touch voltage is 1080 V, both under worst case conditions
- because the step and touch voltages are below the maximum values given by the governing standards, the situation is to be considered safe regarding these aspects. This includes the situation of excavating works close to the short circuit location.

6 TOPIC 5: MAGNETIC FIELD STRENGTH

As a last safety aspect considered in this study, magnetic fields around the power cable circuit are considered. It has been agreed between EirGrid, Rush Community Council and KEMA to use ICNIRP guidelines to define the limitations to the magnetic fields generated by the cable circuit. As the converter stations were still in the design phase at the start of this study, the magnetic field limitations following from the ICNIRP guidelines are used to calculate limitations on the current flowing through the cables at a certain frequency. These limitations can be used as requirements for the converter stations.

6.1 ICNIRP guidelines

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has issued guidelines for limiting the exposure to static and time varying electric and magnetic fields up to 100 kHz. ICNIRP frequently updates these guidelines. The latest updates are very recent:

- document *"Guidelines for limiting exposure to time varying electric and magnetic fields (1 Hz – 100kHz)*" was published in December 2010, with an erratum issued on 25-11-2010
- document *"Guidelines on limits of exposure to static magnetic fields",* published in April 2009.

With power cables, there is no external electrical field outside the power cables, but there is an external magnetic field present. ICNIRP issued guidelines in the above mentioned documents to limit the magnetic flux density, thereby distinguishing between the general public and occupational exposure. Other sources indicate that when the general public exposure limitations for time varying fields are used for 50 Hz fields, there will be no resulting effect on medical devices such as metallic protheses, cardiac pacemakers and implanted defibrillators and cochlear implants. Furthermore, ICNIRP has used reduction factors in establishing guidelines to allow for some uncertainty in scientific data. This results in a set of guidelines which can be used to assess the safety of the magnetic field around a power cable circuit for the general public.

The maximum magnetic flux density for static fields for the general public is 400.000 μT (400 milli Tesla). ICNIRP notes that the IEC restriction levels can be as low as 500 μT to prevent effects in implanted electronic / ferromagnetic medical devices.

For time varying fields, the maximum magnetic flux density for the general public according to ICNIRP is given as a function of the frequency of the magnetic field in Figure 8. The maximum magnetic flux density at 1 Hz is 40.000 μT.

In between 0 Hz (static field) and 1 Hz (slow time varying field), no guidelines are given.

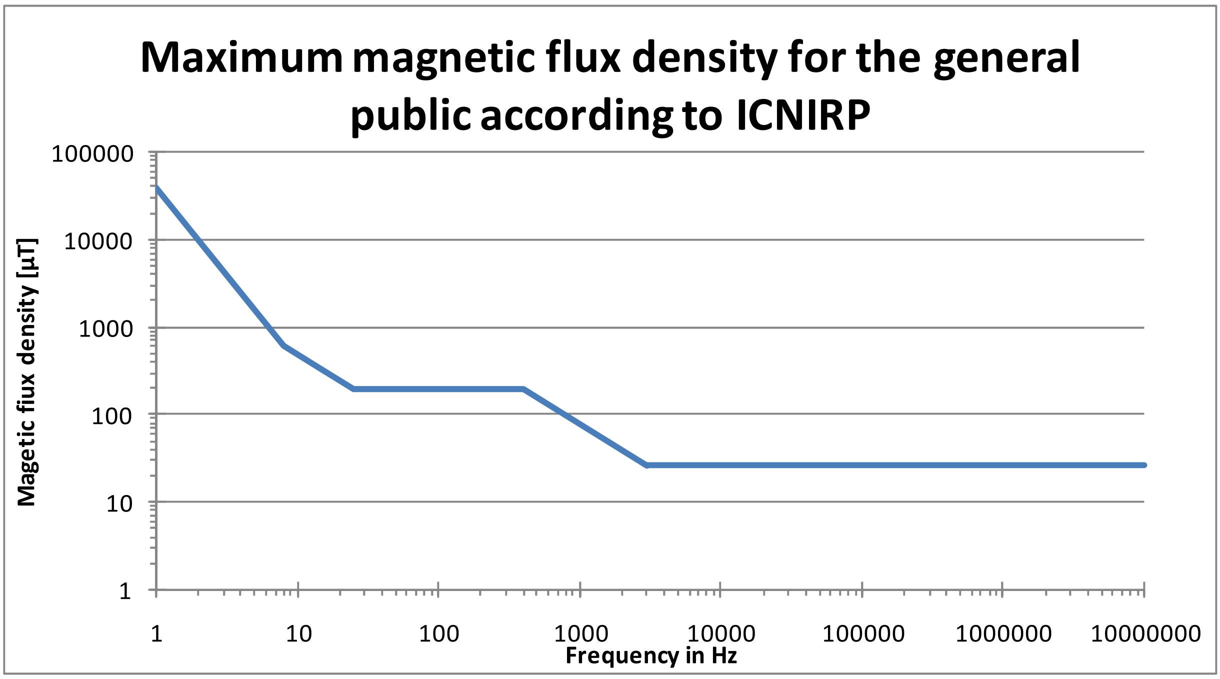

Figure 8: The maximum magnetic flux density of time varying fields for the general public according to ICNIRP.

The maximum magnetic fields mentioned assume exposure to a uniform field, in which the body experiences the same flux density throughout the body. For underground power cables, the field diminishes significantly with an increasing distance from the power cables, leading to non-uniform field exposure. In these cases (according to ICNIRP), taking the maximum magnetic field in the space occupied by a human body and checking this maximum field against the limitations given above, always results in a safe, but very conservative exposure assessment. This reasoning has been used to perform the assessment in this report: using the maximum field in the space occupied by a human body, and assuming that this maximum field is present throughout the body. Note that the maximum field around the buried East-West interconnector will be at the ground surface.

6.2 Static magnetic field strength

The magnetic field strength around a power cable circuit can be calculated using:

$$B = \frac{\mu I}{2\pi r}$$

B : magnetic flux density in Tesla
μ : magnetic permeability of the material (1 for air, soil, water, humans)
I : current through the power cable in Amperes
r : distance between the power cable and the point of observation in meters.
Note that the current has a certain direction, and the magnetic flux density has a direction as well.

With a bipolar HVDC cable, the currents flowing through the conductors of both power cables are equal in magnitude, but opposite in direction. If the cables would be in exactly the same position, the total magnetic field (which can be found by vector addition of the different contributions) resulting from the power cable circuit, will be exactly zero. Because in reality the cables are spaced, there is a remaining magnetic field around the power cables. This shows that keeping the cables closely spaced will result in low magnetic fields.

In the town of Rush, the following situation is present:

- the cables are spaced 250 mm apart
- the cables carry a current of 1300 A or less (520 MW at ±200 kV).

In Figure 9, the magnetic field above the power cable circuit is given as a function of the distance to the power cable. The flux density is given in micro Tesla [μT]. Both the vertical distance (cable depth) and the horizontal distance are given in the figure. Different cable depths are represented by the different lines in the graphs. The vertical distance given is the distance between the road surface and the heart of the power cable. Different horizontal positions with respect to the cables are presented via the x-axis. This axis gives the horizontal distance between the center of the cable circuit, and a certain location of interest.

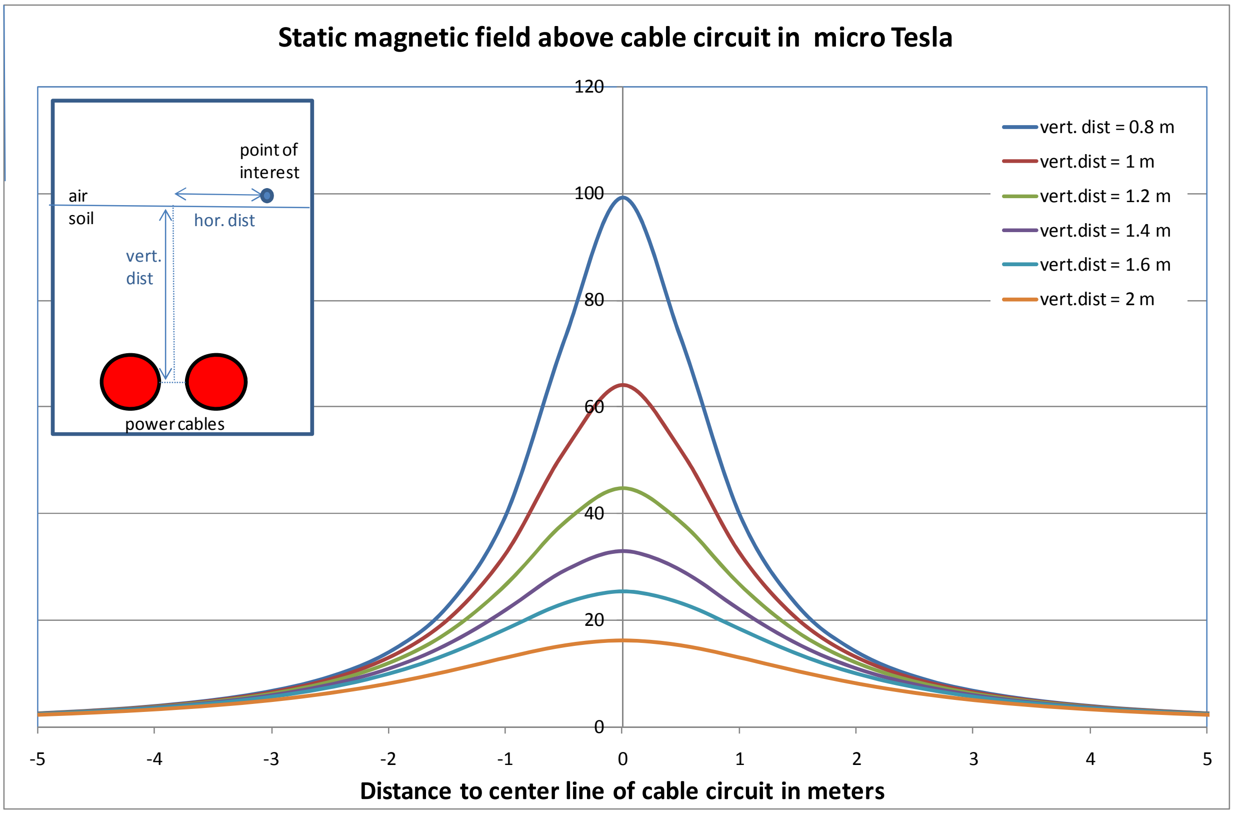

Figure 9: The magnetic field above the HVDC bipole cable circuit in micro Tesla, as a function of the cable depth (vertical distance) and horizontal position.

Typically, the burial depth of the cables in the town of Rush is more than 1 meter, the shallowest burial is ~0.9 meters. Houses and other buildings are typically a few meters away. The closest house has a distance of ~1.5 meters from the center of the cable circuit.

Compared to the limitations given by ICNIRP, the static magnetic fields which can be expected on the surface level are much lower than the limitations. Furthermore, the magnetic flux density of 60 μT is also much lower than the value of 500 μT mentioned by ICNIRP as the restriction levels per IEC for people with implanted electronic / ferromagnetic medical devices. Note that the ICNIRP restriction level for people without implanted medical devices is 400.000 μT (400 milli Tesla).

In the case of a bend in the cable route, the magnetic flux density might be increased due to superposition of different magnetic field contributions. In the town of Rush, the situation shown in Figure 10 is present showing a near 90 degree bend in the cable. At a certain point near the cable, there will be a magnetic field contribution due to both the horizontal and the vertical sections of the cable route. However, as the bending radius of the cable has the same order of magnitude as the magnetic field curve shown in Figure 9, KEMA expects the total increase of the magnetic fields due to the bends will be small. The top values will remain as stated in Figure 9, while one of the slow decaying ‘shoulders’ of the curve will be lifted with a value of maximally a few micro Tesla.

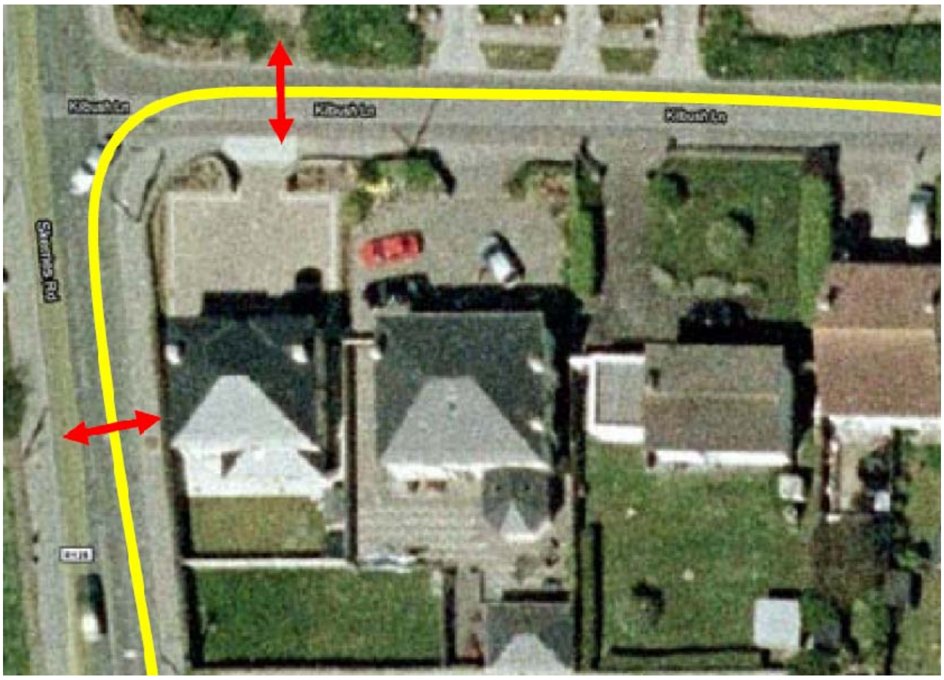

Figure 10: 90 degree bend in the cable at Skerries road en Kilbush lane.

6.3 Time varying magnetic field limitation

Next to the static magnetic field generated by the HVDC cable circuit, the cable circuit will also generate time varying magnetic fields due to time varying currents superimposed on the DC current, called the ripple, due to transients or due to changes in the transported current.

The limitation for time varying magnetic fields is given by ICNIRP (section 6.1). For convenience, Figure 8 has been translated to a limitation on the current at a certain frequency through the power cable circuit, anticipating a minimum burial depth of 900 mm, and a spacing of 250 mm. The result is presented in Figure 11.

Example: Figure 11 shows that at a frequency of 100 Hz, a current of 3300 A could be transported through the cable without crossing the ICNIRP guidelines.

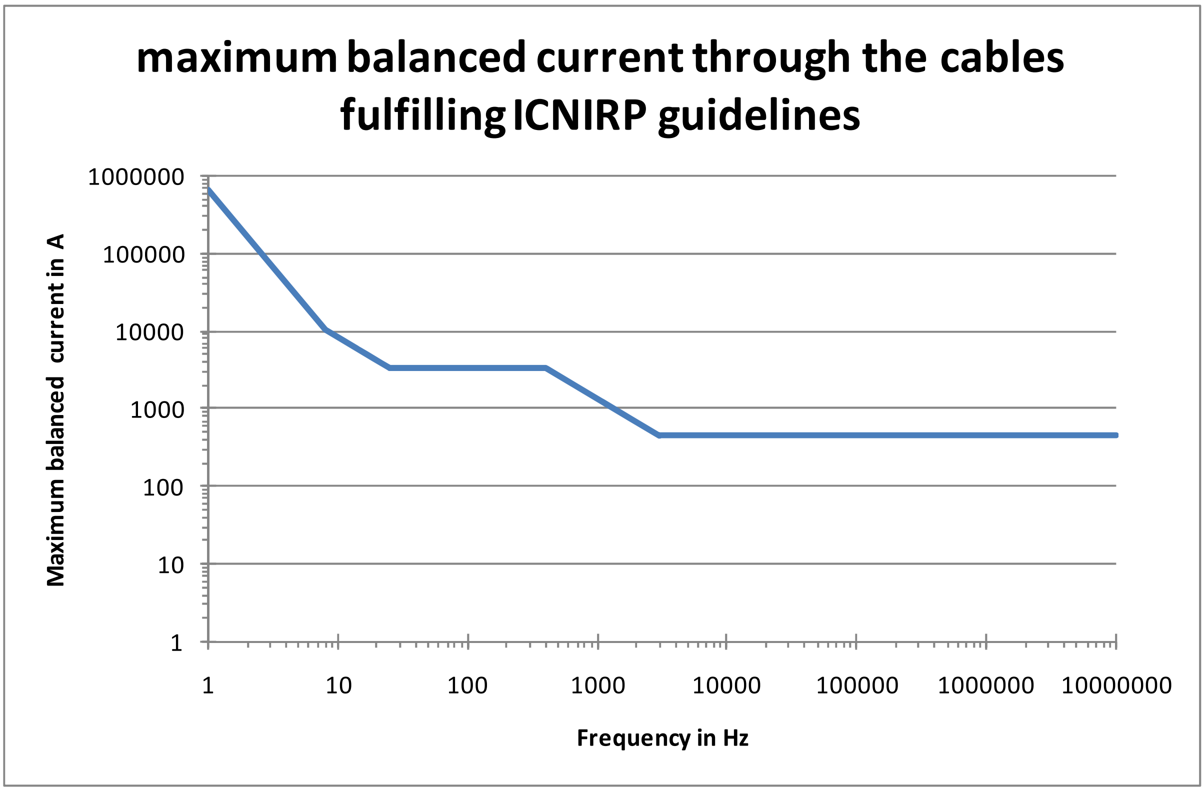

Figure 11: The maximum balanced current through the cables at a certain frequency fulfilling ICNIRP guidelines.

When multiple AC fields are present, ICNIRP states that all contributions should be translated to a relative dosis and added together according to:

$$\sum_{j=1Hz}^{10MHz} \frac{H_j}{H_{R,j}} \leq 1$$

H : magnetic field strength at frequency j

$H_{R,j}$: magnetic field strength limitation by ICNIRP.

As the relation between magnetic field and current is linear, the formula above can be changed into:

$$\sum_{j=1Hz}^{10MHz} \frac{I_j}{I_{R,j}} \leq 1$$

I : current through the East-West interconnector at frequency j

$I_{R,j}$: current through the East-West interconnector deduced from ICNIRP acc. to Figure 11.

Figure 11 shows that in order to exceed the ICNIRP guidelines with the East-West interconnector, a very significant amount of current must be transported in AC frequencies. This is something which is not expected with an HVDC cable system. The vast majority of the current will flow as a DC current, and there might be some smaller AC contributions at higher frequencies. This could be validated by information from Eirgrid:

- the maximum ripple at a certain frequency is 22 A. Compared to a DC current of 1300 A at the converter station, this means an AC ripple of 1.7% of the DC current magnitude
- the root sum squared of the first 200 harmonic frequencies gives a sum of 37.5 A, showing that for other frequencies the AC ripple remains low.

Furthermore, since the ripple currents are given at the converter station, the magnitude of the AC ripple will be smaller than given above in the town of Rush, due to normal attenuation over the cable length. KEMA can therefore state that the AC contributions are orders of magnitude smaller than the maximum contribution per frequency given in Figure 11.

The summation of all contributions per frequency using the formulae presented above will give a definite answer to the question if the AC ripple complies with the ICNIRP guidelines. KEMA can not make this summation because of missing detailed input information, but given the low root sum squared of the first 200 harmonics of 37.5 A, KEMA does not believe that the AC ripple total contribution comes close to the ICNIRP limits.

Changes in the transported current

Changes in the transported current will be bound by a so called ramping rate. The power can not be adjusted quicker than this ramping rate in normal operation situations. This normal operation ramping rate is expected to be 10 MW/minute. This will give rise to a time varying magnetic field, with a maximum amplitude of ~60 μT (see section 6.2, maximum DC field), with a frequency in the range between 0 and 1 Hz. In this frequency range, there are no guidelines from ICNIRP. If however, the maximum amplitude is compared with the limitations at 1 Hz, which is a lower limit, 500 μT, again there is a large difference in between the expected magnetic fields in reality and the maximum magnetic fields advised by ICNIRP.

6.4 Conclusions

The magnetic fields generated by the HVDC cable can be considered to be very low compared to the ICNIRP guidelines. There are large differences in between the advised maximum magnetic field and the expected magnetic field in reality, for DC fields and time varying fields due to ripples, transients or changes in the circuit loading.

EirGrid's filter design shows that a small AC ripple will be present on the DC current. Given the low root sum squared of the first 200 harmonics of 37.5 A, KEMA does not believe that the AC ripple total contribution comes close to the ICNIRP limits, but can not proof this (no detailed input data). KEMA advises to calculate the summated contribution and to verify this against the ICNIRP guidelines, with the formulae and limitations presented, now that the design of the converter stations is recently finished.

7 FINAL CONCLUSIONS

With assessing the five different safety aspects reported in this document, KEMA has come to the conclusion that the East-West HVDC interconnector is obeying all assessed safety limits with a significant margin, with few remaining assumptions. Compared to international experience with other HVDC and EHV AC cable circuits, the East-West interconnector is to be regarded as a very safe cable system. This main conclusion is substantiated by the following sub conclusions, mentioning the remaining assumptions as well:

Chances on cable failures

- Compared internationally, the way the HVDC cables in the town of Rush are protected against third party damage is rather good.
- The failure rate of the total route of the HVDC cable circuit through the town of Rush is expected to be significantly lower than 0.005 failures per year.
- During the site visit KEMA found no evidence for inaccurate or careless installation procedures resulting in failures or future failures. Therefore, KEMA assumes that installation, installation supervision, cable location recordings, and information exchange to excavators carrying out works in the vicinity of the East-West interconnector is performed according to best practices. This has not been fully checked within the scope of this study.

Trench layout and mechanical protection

- In general KEMA's impression of the mechanical protection of the HVDC power cable circuit through the town of Rush is rather positive. Multiple measures have been taken to minimise the risk on mechanical damage. Compared to other cable circuits in Europe (e.g. 400 kV AC), for reference, this cable circuit is protected very well.
- KEMA did not assess the quality of the installation performed and can therefore not assess the complete as built situation. However, the site visit conducted did not result in doubts regarding this issue.

Effect of a cable or joint failure

- During a short circuit, there are Lorentz forces acting on the cables throughout the cable circuit. The cables will not move upwards or sidewards, and will stay inside the ducts.
- At the location of a short circuit (cable or joint failure), the dissipated energy is ~40 kJ. This energy dissipation is relatively modest.

- Failures in other cable circuits with a very similar dissipated energy show almost no effects outside the power cable. It is therefore expected that only the power cable or joint and the first few cm of soil directly around the power cables (inside the ducts) may become affected at a possible failure location in the East-West interconnector. This will not affect any other infrastructure that is outside this zone of a few cm of soil.

The earth potential rise, step and touch voltages generated during a cable failure

- The Earth Potential Rise during a cable or joint failure (short circuit) is 1350 V.
- Regarding the step voltage, the requirements given by the governing NEN-EN 50522, IEEE 80-2000 and IEC 60479-1 standards are met. The step voltage is lower than 1350 V while the maximum permissible step voltage is 2800 V, both under worst case conditions.
- Regarding the touch voltage, also the touch voltage meets the requirements stated in the governing NEN-EN 50522, IEEE 80-2000 and IEC 60479-1 standards. The touch voltage is maximum 590 V while the maximum permissible touch voltage is 1080 V, both under worst case conditions.
- Because the step and touch voltages are below the maximum values given by the governing standards, the situation is to be considered safe regarding these aspects. This includes the situation of excavating works close to the short circuit location.

Magnetic fields

- The magnetic fields generated by the HVDC cable can be considered to be very low compared to the ICNIRP guidelines. There are large differences in between the advised maximum magnetic field and the expected magnetic field in reality, for DC fields and time varying fields due to ripples, transients or changes in the circuit loading.
- EirGrid's filter design shows that a small AC ripple will be present on the DC current. Given the low root sum squared of the first 200 harmonics of 37.5 A, KEMA does not believe that the AC ripple total contribution comes close to the ICNIRP limits, but can not proof this (no detailed input data). KEMA advises to calculate the summated contribution and to verify this against the ICNIRP guidelines, with the formulae and limitations presented, now that the design of the converter stations is recently finished.