Assessment of the Technical Issues relating to Significant Amounts of EHV Underground Cable in the All-island Electricity Transmission System

Summary Report

November 2009

Tokyo Electric Power Company

Technical Report on using EHV cables as alternatives to Overhead Lines November 2009

THE REPORT AND THE CONSULTANT

The contract for producing the Technical Report on the use of extra high voltage (EHV) cables in the island networks was awarded to Tokyo Electric Power Company (TEPCO) following an open tendering process. TEPCO designed and operate the longest (39.5km) EHV cable in any country up to this time. TEPCO have done extensive research on the issues involving cable networks as users of significant cable networks especially in urban areas.

THE DATA AND ASSUMPTIONS

There is a limit to the accuracy which can be entered into at the feasibility stage, because study engineers would need the manufacturers' models for real components (transformers, reactors switchgear etc.). When conducting normal power flow analysis approximate models are used because very detailed modeling of a wide network is not feasible. However, to study many of the issues involving the energisation of long EHV cables and their performance during and after faults it is necessary to understand equipment in a lot more detail. NIE, EirGrid and TEPCO have co-operated to model the network to the level of detail required and would like to also express thanks to Dr. Nasser Tleis at NGrid UK for assistance with some modeling information. A sensitivity analysis has also been carried out on important model parameters to ensure the robustness of the modeling and the assumptions made.

THE QUESTIONS ANSWERED

Three basic questions were posed to TEPCO:

- What is the potential impact on the all-Island transmission system of installing considerable lengths of EHV cable, either individually or in aggregate?
- Is it feasible to install 400kV cable instead of overhead line as a link between Turleenan in NI and Kingscourt in Co. Cavan and on to Woodland near Dublin?
- Is it feasible to underground parts of a Turleenan – Kingscout – Woodland 400kV overhead line circuit?

GENERAL POINTS

Reactive Power

EHV cables are very capacitive in nature. Capacitance forces the voltage upwards, so if uncompensated, the voltage at the receiving end an EHV cable will be considerably higher than the voltage at the sending end. Even by compensating for the capacitance at each end of the cable, the voltage somewhere in the centre of the cable can become unacceptably high and prematurely age the cable insulation. Compensation for the cable's capacitance takes the form of large coils or reactors which connect the cable cores to earth.

In the study (as explained below) reactors are fitted to compensate the capacitive nature of the cables. Reactors are fitted to the cable rather than the busbar, so that if the cable is energised or de-enegised, the reactor is connected / disconnected along with it. This reduces the risk of overvoltage when one side of the cable is open circuited. For smaller cables it would be reasonable practice to connect the reactors separately to the busbars so as to give flexibility in the control of reactive power for a range of purposes.

Resonance

EHV cables have high levels of capacitance across the insulation which is between the conductor and the external sheath. This capacitance will resonate with the inductance of the external system at a particular frequency.

The resonant frequency occurs when the capacitive reactance is equal to and opposite of the inductive reactance. A resonance is the half-cycle exchange of energy between the electric field of the capacitance, and the magnetic field of the inductance. If a resonance is excited by an external disturbance, dangerously high voltages can occur.

A weak system with long cable creates low frequency resonances. For long EHV cables, it is typical to have high levels of reactive compensation to manage the cable reactive power and voltage profile. This contributes further to low frequency resonances.

Since the power system supplies energy at 50Hz, it would be disastrous if 50Hz was the resonant frequency. But there are various other key frequencies to be avoided. Most of these are multiples of 50Hz. While the power system normally operates at 50Hz, its actual frequency or speed can vary between 48Hz and 52Hz during system abnormal operation. So multiples of frequencies in that range could be a problem.

Question 1 - What is the potential impact on the all-Island transmission system of installing considerable lengths of EHV cable, either individually or in aggregate?

In answering the first question TEPCO have looked at a long 400kV cable in a part of EirGrid's system which is not close to the major sites of generation. The circuit selected goes from Kilkenny – Cahir – Aghada. Choosing a long cable in a weaker network area is considered to highlight any critical issues. TEPCO have therefore studied this link in detail. Most other new or replacement circuits for 2025 have been simulated as EHV cables during this study. This corresponds to a scenario with high levels of EHV cable within the joint transmission network

REACTIVE POWER AND VOLTAGE MANAGEMENT

TEPCO considered a long cable in a weak part of RoI network with a large amount of other cables in order to determine whether there are any systemic problems. Reactive balance for the cable sections can be achieved. To maintain voltage profile within the long cable section at a safe level an additional substation with seven reactors is required half way between Cahir and Aghada. This enables the voltage to be managed within the limits required by license standards.

EHV cables are very capacitive in nature. Capacitance forces the voltage upwards, so if uncompensated, the voltage at the receiving end of an EHV cable will be considerably higher than the voltage at the sending end. Even by compensating for the capacitance at each end of the cable, the voltage somewhere in the centre of the cable can become unacceptably high, which will prematurely age the cable insulation amongst other things. Compensation for the cable's capacitance takes the form of large coils or reactors which connect the cable cores to earth. TEPCO found that the 400kV cable solution Kilkenny – Cahir – Aghada required 24 reactors totaling 2080MVAr to fully compensate the cable capacitance. Switching in or out a reactor should not result in a step change of voltage greater than 3%, so the required reactance has been provided by a large number of reactors in each location. TEPCO place 4 reactors in Kilkenny, 8 in Cahir and 5 in Aghada. In addition a new 400kV station is required midway between Cahir and Aghada to house 7 reactors to keep the cable mid-point voltage to an acceptable level. It is important to consider the voltage when one reactor is out of service. Under these conditions further switching or faults must not result in a step change of more than 10%.

RESONANCE

As stated in the general points, when the cable resonant frequency is excited, severe overvoltages can occur inside the system and this can lead to damage. TEPCO therefore have modeled over-voltages in considerable detail.

<u>Series resonance</u>

Series resonance is not a problem in the study area.

When a circuit is energized, the surge of power into the circuit creates noise at a number of characteristic frequencies. One or more of these frequencies can cause the cable and the surrounding system inductance to resonate.

However this resonance can be detuned. Detuning moves the resonance frequency of the cable and reactor system away from the danger points. The simplest way is to adjust the percentage reactive compensation of the cable to avoid the resonant position.

If the cable is connected to transformers at the receiving end and the lower voltage sides of those transformers are connected to cables, then it is possible for the resonant frequency of energizing the cable to excite resonance in the lower voltage systems. This is called a series resonance.

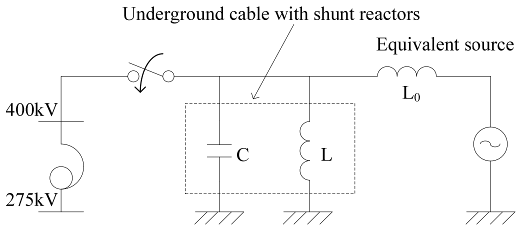
For the Kilkenny – Cahir – Aghada cable circuit, there are plans for a new 220kV circuit on Kilkenny-Laois. If it were cable it forms a potential resonance circuit with the 400/220 kV transformers in Kilkenny. This option has not been investigated as the Woodland-Kingscourt-Turlenaan 400kV series resonance has been considered as more severe.

Parallel Resonance

A resonance frequency between 50 and 100 Hz can threaten the project. A combination of factors determines whether the resonance frequency approaches to 50 and 100 Hz, e.g. network topology, compensation patterns, load / generation scenarios and cable length.

In the Kilkenny-Aghada-Cahir case, TEPCO identified serious and threatening issues when the Cahir – Aghada cable is shortened to half of its original length. This would require more extensive investigation if such a solution was to go forward.

A further type of resonance can occur on the system and is more difficult to determine. The cable acts as a capacitance to earth. The reactors are coils connected to earth. The remainder of the system behaves as a reactor. The system as represented by a reactor will resonate with the cable and its compensation reactors at a particular frequency. This is called parallel resonance.



As the system is constantly changing, because of the number of generators connected and the operational configuration, this resonant frequency will change.

It is only practicable for study engineers to examine a few cases to determine if there is resonance, but a wide range of conditions will exist in practice. The approach which TEPCO have taken is to reduce the rest of the system to a single generator and the lines, cables and transformers in the system to a single reactor. It is then possible to vary the size of this reactor to emulate different system conditions.

For the Kilkenny – Cahir – Aghada cable circuit TEPCO report that a parallel resonance occurs at about 75Hz but depending upon system configuration, this can move to 88Hz. This corresponds to going from a weak system through to a strong system.

If the resonance frequency is between 50 and 100 Hz, certain operating conditions could trigger parallel resonance conditions at 100 Hz, i.e. a change in the amount of cable, a stronger system or a combination of the two. For instance, TEPCO found that if the Cahir – Aghada cable is shortened to half of its original length, this could create a parallel resonance at 100Hz. This would be serious because it is at a dominant frequency of transformer energisation current. The same would be true for the part cabled solution where 50% of the line is cabled.

The result shows that the temporary overvoltage (TOV) level would put the cable system at risk as it is well above the conventional IEC 62067 AC voltage test of 260 kV r.m.s.

In addition, TEPCO performed a surge arrester adequacy evaluation, aimed at verifying the suitability of its designed energy capability and not at testing its efficiency for protecting the network from temporary overvoltage (TOV). The study showed that the present equipment capability is not adequate.

TEPCO have performed sensitivity checks to see if this important result is sensitive to the characteristics of the transformer and to the amount of load on the system at the time. TEPCO conclude that, in this case, the dangerous condition persists in all studies except one least severe case when a different magnetic hysteresis characteristic is chosen.

If only a part of the system is cabled the resonance frequencies also change to line around the area of the fifth and seventh harmonics, which is the region of known harmonic energisation.

<u>Resonance in Line Energisation</u>

Parallel resonance in line energisation is not a problem in the study area.

TEPCO have considered energisation in sections of the entirely cabled route. Dangerous conditions may arise when parallel resonance frequency of the network matches frequency contained the line energisation overvoltage. Due to the low parallel resonance frequency 75 – 88Hz, unreasonably long cable would be required to achieve the match.

TEPCO have found resonance on line energisation is not a problem.

<u>Resonance in islanding of the cable system</u>

The results of islanding of a small part of the system including the cable are not desirable. In this case further analysis is required.

TEPCO considered what would happen if the generation at Aghada and the local system up to the end of the 400kV cable were to become islanded from the larger system. The results are not desirable. There are large amounts of 80Hz-90Hz resonant voltages in the system during the disconnection transient. The system voltage waveforms are almost unrecognizable with high harmonic content and the remaining system had low damping. The amount of reactive compensation connected to the cable is also a significant factor in determining the shape of the waveform and extent of the problem. Overall, it seems important not to allow this condition to occur.

TRANSIENT VOLTAGES ON ENERGISATION

Transient voltages on energisation do not threaten the project.

When a cable is energized the transient which occurs can cause overvoltages within the cable. TEPCO have studied this for the Kilkenny – Cahir – Aghada circuit. Various factors affect the level of overvoltage: firstly the timing of the circuit breaker closure relative to the system voltage wave and also the precision of the timing between phase circuit breakers. TEPCO have studied this statistically by randomizing both the closing time and the interval between phase closures. The closing time was randomized through the 20ms that is one cycle, whereas the phase out-of-balance timing had a standard deviation of 0.001s. No severe issues are reported.

When a cable fault occurs, the position of the fault in the cable and the timing of the fault and interruption relative to the system voltage waveform will all be issues determining the transient voltages which will appear. TEPCO have studied this and varied the amount of cable in the circuit and the amount of compensation. The voltages are within the withstand capability of equipment [Switching Impulse Withstand Voltage (SIWV) = 1050kV for 400kV equipment] and therefore not seen as a problem. However, the voltage waveforms can have large harmonic content between 70 and 120Hz and low damping which may affect other equipment operation or protection relays.

SUDDEN LOSS OF A CABLE – IMPACT ON SYSTEM VOLTAGE

System voltages can be maintained within limits for the sudden loss of the cable circuit providing compensation rate is greater than 90%.

If a 400kV cable is suddenly put out of service, there could be an impact on the system voltage. This could give rise to a voltage step change outside the (frequent switching 3% or contingency 10%) allowable range. In extremis the loss of a cable could give rise to voltage instability. The amount of cable, the loading of the system, and the reactive compensation rate are all key factors. No issues were seen on the Kilkeeny – Cahir – Aghada circuit provided that the circuit was close to 100% compensated. The highest step change is seen at Cahir or Aghada. The 3% step change is violated if the cable reactive compensation rate is less than 90%. If the cable compensation rate reduces to 70%, the step change in voltage exceeds 10% for loss of the cable between Cahir and Aghada. The loss of the Cahir – Aghada line leads to a loss of reactive power in the area. A locked tap analysis was performed to determine whether there was good voltage stability margin on the loss of the circuit. It was concluded that the winter peak load in the area could be increased by 50% (or 25% without generators at Glanagow and Longpoint). This is deemed a good stability margin.

BLACK START

Black start for the RoI system with this amount of cable is a problem for some black start islands. The NI system seems not to suffer from a similar difficulty.

TEPCO studied black start effects with large amounts of cable on the system.

- In particular for this analysis TEPCO studied the ability to black start the NW and west of ESB system from local generators. In the analysis a number of circuits in the area were cables. To start the system it was assumed that shunt capacitors and SVCs were out of service. It is normal practice when energising this type of system from black start conditions to maintain an acceptably low generator voltage until the load is connected. In this case to remain within generator reactive power capability, the generators have to be operated at about 40% voltage.
- Some black start stages have resonance frequency around 100Hz; no transformer energisation is recommended at these stages.
- In the NI system the study relates to the NW black start island. Coolkeeragh generators are started, then the proposed 275kV cable to Strabane is energised and finally the 275kV cable to Omagh is energized. Generators remain within reactive power limits throughout the process providing the cable reactive compensation exceeds 85%. There are some resonance frequencies which could be a problem. In particular there is a very sharp resonance frequency between 166 and 168Hz. And one at Omagh at between 94 and 97Hz. The latter is rather close to 100Hz for comfort and would need special consideration.

Question 2 - Is it feasible to install the 400kV link between Turleenan in NI and Kingscourt in Co. Cavan and on to Woodland near Dublin, a total of 140 km, as 400kV cable instead of overhead line?

GENERAL ISSUES AND CIRCUIT ASSUMPTIONS

The circuits will together form an important link between an electrically strong point on the NI transmission system and a very strong node near Dublin in the RoI transmission system. They therefore will form an important element in securing market flows and energy variability management on the all-island transmission system. The link is required to back-up the loss of the existing 275kV double circuit overhead line route which has a capacity in the region of 1500MVA.

1500MVA is a very large transfer on a single cable. Such transfers have been achieved at about 400kV in London and Madrid but not over this distance 140km (London 20km of single circuit and Madrid 12.8km of double circuit).

Two cable construction options have been considered as meeting the capacity requirement – one 2500mm^2 Milliken copper cable or two 1400mm^2 aluminum cables. The selected cable spacing is 500mm between phases with the cables laid flat for the aluminum double circuit option and 700mm between phases with the cables laid flat for the single circuit Milliken option. The Milliken option used copper enameled wire. This link will require a significant number of joint bays, between 800 and 1200, and so will have reliability implications.

The maximum soil temperature was assumed to be 15^{0}C, the cable was assumed to be buried at 1.3m depth. Substations are assumed to be earthed to 1 ohm and each normal joint to 5 ohms. The sheath circuits are assumed to be cross bonded. Other assumptions are within the main report. The values for resistance, reactance and susceptance are given in the main report.

REACTIVE POWER

Reactive balance for the cable sections can be achieved. For a more efficient power transmission, there should be an intermediate substation half way between Turleenan and Kingscourt.

TEPCO found in the case of the North-South 400kV Interconnector, all 140 km undergrounded, the following outcomes:

- the best system voltage control is achieved when the cable capacitance is 100% compensated;
- the cable voltage needs to be managed for a range of conditions including normal operation, light load operation and tripping one end of the cable circuit.

The situation will be more onerous if some of the reactive compensation is out of service.

In the case of the <u>double circuit</u> aluminum cable option the circuits together generate the following reactive power:

Woodland – Kingscourt section
1080MVAr
Kingscourt – Turleenan section
1525MVAr
Therefore the total requirement is 2605MVAr

The optimum compensation for the route is:

- four 150MVAr reactors in Woodland Substation near Dublin,
- four 120MVAr and four 100MVAr units in Kingscourt
- four 100MVAr units in Turleenan in NI.
- In addition, to increase power transmission efficiency, it was optimal to install six 120MVAr units about halfway between Kingscourt and Turleenan. This requires an extra 400kV station.

This totals 2600MVAr which equates to 100% compensation.

In the case of the single circuit 2500mm Milliken copper cable the circuit generates:

Woodland – Kingscourt section
700MVAr
Kingscourt – Turleenan section
990MVAr
Therefore the total requirement is
1690MVAr

The optimum compensation for the route is:

- two 200MVAr reactors in Woodland Substation near Dublin
- four 150MVAr units in Kingscourt
- two 150MVAr units in Turleenan in NI.
- two 150MVAr units about halfway between Kingscourt and Turleenan. This requires an extra 400kV station. The total compensation is therefore 1600MVAr.

This equates to 95% compensation overall (100% in the Woodland – Kingscourt section and 91% in the Kingscourt – Turleenan section).

While it may be technically possible to avert the mid point compensation on the Woodland to Kingscourt section this would give rise to operational inflexibility and increased losses.

RESONANCE

As stated in the general points, when the cable resonant frequency is excited, large voltages can occur inside the system and this can lead to damage. TEPCO therefore have modeled over-voltages in considerable detail.

Series resonance

Nothing in the series resonance study threatens the project

Extensive series resonance studies have been carried out, although it must be pointed out that the 275 and 220kV system data has been obtained from PSSE and distributed parameter models have thus been created. In any case, the NI system has no 275kV cable in the vicinity of the interconnector. There is 220kV cable in Dublin.

TEPCO considered that the most likely excitable series resonance condition might be with 400/220kV transformers and the 220kV cables in the Woodland area. TEPCO have however also examined series resonance of the system in Kingscourt and around Turleenan.

In Woodland there was a resonance position for system normal operational configuration at about 380Hz. However, energisation of the 400kV cable system caused weak excitation of the 220kV system. Put another way, the amplification ratio was very small and thus the resonance overvoltage on the 220kV system was not significant. Under certain conditions a further resonance position could be found at 200Hz. This is a significant frequency as it is a transformer energisation frequency, but nonetheless the amplification ratio was small and thus the overvoltage was not significant. TEPCO tried increasing length of the cables to determine how far the system was from a serious resonance. Cable length needed to be more than doubled and the resonance still did not result in a significant overvoltage.

A number of weak resonant frequencies were seen in NI but none threaten to give rise to severe overvoltage.

Parallel Resonance

TEPCO's conclusion for the double circuit cable option is that the parallel resonance overvoltage is not at a level to threaten the project. However, in arriving at this conclusion, TEPCO have made two critical assumptions. Firstly, we have assumed that the design and operating standards used in Japan can be applied in the EU and secondly, that equipment to control not yet developed or in production can be engineered for the project.

To summarise the issues for the Woodland – Kingscourt – Turleenan circuit:

- the double circuit cable system has four parts (two circuits from Woodland – Kingscourt and two from Kingscourt to Turleenan) and therefore depending upon which parts are in or out of service the possibilities of creating a resonance are greater.
- The circuit between Kingscourt and Flagford must also be considered as part of the system.
- The impedance of the rest of the system (as seen from Woodland, Kingscourt and Turleenan) varies from summer off-peak to winter peak.
- Energising transformers and switching can both create the circumstances for injecting non-50Hz frequencies into the system. Transformer energisation has a high 2nd harmonic (100Hz) component in the wave.

The worst parallel resonance overvoltage seen from Woodland substation was when the external system was weakest (summer off-peak) and with overhead line outages. The resonance occurred at 90Hz. The significant overhead line outages are Woodland – Oldstreet and Kingscourt – Flagford circuits.

Parallel resonance was examined for all operational combinations of the double circuit option. This is done by adjusting the operational configuration of the remainder of the system to achieve a resonant condition at 100Hz. The resulting transient system overvoltages for this case are high (up to 542kV peak). Surge arrestor's adequacy evaluation shows that the energy absorption is within limits. The timing of closing the circuit breakers is not significant.

At Kingscourt and Turleenan, the same analysis was carried out and simulations showed the temporary overvoltage (TOV) to peak at 516kV at Kingscourt and 530kV at Turleenan. Again, this does not cause the surge arrestors to operate in low impedance mode.

The analysis was repeated for the single circuit (Milliken) cable option. This analysis showed a resonance condition to occur at about 102.7Hz which is very close to the transformer energisation second harmonic. The worst transient overvoltage seen on transformer switching was 530.9kV.

These waveforms show 1.7 Uo RMS TOV with very little damping within 1-5 seconds. According to EU cable design practice, this will necessitate the after laying AC testing of the cable at a higher voltage than normal practice [IEC62067], i.e. 1.7 Uo. Moreover, as TOVs propagate easily in the HV system, this can also demand a thorough insulation coordination design level control of existing equipment.

OVERVOLTAGE CAUSED BY THE SYSTEM ISLANDING

The level of overvoltage does not threaten the project.

In this condition the cable system is somehow separated from either the NI system or the RoI system. TEPCO have studied this for all operational configurations of both cable options.

The conclusions are that the worst case overvoltage occurs in the Kingscourt end of the cable system resulting from islanding at Woodland side and is 600kV. It is not sustained due to a rapid decay characteristic and can be compared with SIWV [Switching Impulse Withstand Voltage = 1050kV for 400kV equipment].

LINE ENERGISATION AND FAULT OVERVOLTAGE

Line energisation and Fault overvoltage does not threaten the project.

The severest condition for assessing line energisation overvoltage is when the other connected circuits are out of service, so that the overvoltage cannot be propagated away from the stressed circuit. The study is voluminous.

Faults are applied for different operational configurations and for different timings in 10^0 steps through 180˚ of the wave form (18 faults) and at 15 positions in the cable system. The fault type is single line to ground (core to sheath) at phase A.

No condition resulted in a switching overvoltage greater than 1.86 pu whereas SIWV is 3.21pu.

$$1.0\,pu = \frac{400kV}{\sqrt{3}}.\sqrt{2}$$

PROTECTION

Protection problems exist but are solvable and so do not threaten the project.

Differential protection may be affected by the charging current, which appears not to pass right through the system. Computation algorithms may be required to bias the relay against operation for this natural phenomenon. TEPCO use negative sequence distance protection as back up. Negative sequence distance protection is not significantly affected by the charging current.

DC OFFSET AND ZERO MISS

DC off-set and zero-miss phenomena will exist and could threaten the ability to safely interrupt fault current. Mitigation measures are available so that the project is not threatened by the problems.

There should be no AC charging current for a fully compensated cable. However on energisation, depending upon the point of wave of switching, there will be a large DC component in the current. This will decay over about 1s. The DC component moves the entire current wave up or down and as such prevents it passing through zero current for more than 1s. If a fault is present or occurs on energisation, the circuit breaker cannot interrupt the fault.

Several countermeasures are possible such as automatic sequential switching, or opening of the circuit breakers on the reactors on detection of the fault. This allows the main system current to pass through zero and the main circuit breaker to operate.

SHUNT REACTOR SWITCHING

Shunt reactor circuit breakers may experience very high voltages but mitigation exists so as not to threaten the project.

Analysis shows that the shunt reactor circuit breakers could fail because it is possible to create re-strike and generate the very-fast-front overvoltage which can be harmful to main transformers, shunt reactors and so on.

Surge arrestors or a shunt reactor circuit breaker timing controller in each phase would need to be fitted. Both options have advantages and disadvantages.

CONCLUSIONS

- A thorough EMT analysis has been carried out; some switching operations have caused temporary overvoltage (TOV) (1.7Uo r.m.s.), due to parallel resonance phenomena, which may threaten the project of totally cabling the route either as a single or a double circuit of capacity 1500MW. In particular it is of concern that the cable as laid cannot be AC tested after laying to the recorded overvoltage withstand level.

Furthermore:

- Care should be taken with protection of long 400kV cable circuits.
- Care is needed in management of reactor switching.
- Care is needed in main circuit switching to avoid current zero miss situations.

Question 3- Is it feasible to underground parts of a Turleenan – Kingscourt – Woodland 400kV overhead line circuit, which is 140 km in total?

GENERAL

In constructing a 400kV circuit, it is sometimes impossible to obtain permissions for parts of the circuit to be constructed as overhead line. That results in a mixed line / cable system. The above question has been posed to consider whether there are any further technical problems arising out of such a system. TEPCO have pointed out that there could be different resonance issues depending upon the compensation rate of the undergrounded cable. There could be problems if the utilities decide to maintain the performance of the mixed system by detecting that a fault was on the overhead sections and using high speed auto-reclosing techniques to achieve rapid restoration of the circuit.

Obviously such a study could expand to try to cover all combinations of overhead lines and underground cables, but it is not meaningful to do so at this stage. It is more useful to determine which issues are material. The Kingscourt – Turleenan line was used to examine the effects because Turleenan is a weaker bus than Woodland and should thus better indicate any issues. Only the double circuit 1400mm^2 aluminum cable option was considered for this study.

Two scenarios were studied on the Kingscourt – Turleenan line. In the first 30% of the circuit was underground cable and the other 70% was overhead line. In the second 60% of the circuit was cable and the rest overhead line. The circuit from Kingscourt to Woodland was considered as overhead line.

The cable section was placed at the Kingscourt end or in the middle of the 400kV Kingscourt – Turleenan line.

REACTIVE POWER

Reactive balance for the cable sections can be achieved. To maintain voltage profile within the long cable section at a safe level reactors are installed at Turleenan and Kingscourt.

TEPCO found for this one 400kV cable solution, in the case of the North-South Interconnector, the following outcomes can be underlined:

- the best system voltage control is achieved when the cable capacitance is 100% compensated;
- the cable voltage needs to be managed for a range of conditions including normal operation, light load operation and tripping one end of the cable circuit.
- When dealing with mixed line / cable systems it is better to under-compensate the cable to prevent dangerous resonance if single phase auto-reclosure is used to maintain a high reliability of the overhead line section.

The complication is that in carrying out the test, the situation will be more onerous if some of the reactive compensation is out of service for any reason.

TEPCO assumed undercompensation for both 30% and 60% cable cases, considering the application of single phase auto-reclosure.

In the case of the double circuit aluminum cable option being studied here:

- when there is 30% cable in the circuit 490MVAr is produced.
- when there is 60% cable in the circuit 933MVAr is produced.

The compensation proposed for the 30% cable case is:

- two 100MVAr reactors at Kingcourt
- two 100MVAr reactors at Turleenan

This totals 400MVAr and the circuit is then 82% compensated.

The compensation proposed for the 60% cable case is:

- two 200MVAr reactors at Kingscourt
- two 200MVAr reactors at Turleenan

This totals 800MVAr and the circuit is then 86% compensated.

Additional shunt reactor stations were deemed not to be required, although additional checks were made in the over-voltage analysis with the shunt reactors at the cable ends.

OVERVOLTAGE DUE FERRANTI EFFECT

A 30% cable solution is possible, but needs careful management. However a 60% cable solution would need significantly more investigation to demonstrate how voltage is to be managed because it can only be operated with all reactors in service to avoid power-frequency overvoltage problems.

Cable 30%

The voltage profile of the circuit is more severe when the circuit breaker at Turleenan is opened, compared to opening at Kingscourt. In both cases the circuit is assumed to remain live from the other end. This can be managed by maintaining the voltage at Kingscourt below 410kV (close to 400kV would be desirable when one reactor is out of service.) The circuit should not be operated with two reactors out of service at Turleenan.

Cable 60%

This situation is much more onerous. The open circuit voltage at Turleenan is just maintained below 420kV in normal condition if the Kingscourt voltage is 410kV. The outage of any reactor makes the situation unacceptable.

RESONANCE

<u>Series Resonance</u>

Series resonance does not threaten the project.

Series resonance occurs where the cable is connected to transformers with the lower voltage side of those transformers is connected to cables, and where the cable energisation frequency of the cable excites the resonance in the lower voltage systems. Since the section from Kingscourt –Woodland is to be overhead line in this scenario, no 220kV or 275kV cable sections are involved in the secondary circuit. Therefore no series resonance condition needs to be considered.

Parallel Resonance

TEPCO's conclusion is that the parallel resonance switching overvoltage is not at a level to threaten the project.

For the 30% cable scenario resonance occurred for the test network at 155Hz and at 113Hz for the 60% cable scenario. The resonance overvoltage was more severe in the 30% cable situation. The surrounding network configuration was adjusted to give resonances of 100Hz and 150Hz. The resonance overvoltages are more severe in the 30% cable scenario with continued voltage amplification in some phases after 2 seconds. Detailed investigations would be required to understand how the range of realistic system parameters may affect such results for a proposed cable section. Any 150Hz (3^{rd} harmonic) would form a circulating current in the transformer tertiary delta winding. The capability of the winding to sustain this current should be checked.

If the cable was fully compensated an open phase resonance would occur at about 50Hz (49.4Hz) which is unacceptable. With the under-compensation, it is shown that the resonance frequency is at 45.4Hz. This phenomenon occurs because two phases remain closed and one is opened before auto-reclosure. It is still possible to compensate the circuit close to 100% by use of special shunt reactors, which can increase the impedance for phase unbalanced conditions. Alternatively three phase rather than single phase auto-reclosure could be employed.

OVERVOLTAGE RESULTING FROM SYSTEM ISLANDING

Overvoltages lie within the withstand capability of equipment and therefore do not threaten the project.

In this condition the cable system becomes separated from either the NI system or the RoI system. TEPCO have studied this for all operational configurations of both the 30% and 60% cable section scenarios.

No unmanageable overvoltages were seen. The highest over voltage occurred in the 60% case at weak system conditions at Kingscourt at about 770kV (2.36pu) and was of short duration. SIWV is 1050kV and therefore the equipment is considered to be operating within its capability.

OVERVOLTAGES CAUSED BY AUTORECLOSURE

Nothing in the reclosure analysis threatens the project.

Auto-reclosure would never be applied to an all cable system. However, in the mixed line, the majority of faults occurs in overhead line portion and is not sustained faults. There is therefore advantage to apply auto-reclosure scheme to the mixed line. In auto-reclosure the cable is re-energised before it is discharged, and in the single phase auto-reclosure only the faulted phase is opened and re-energised. Auto-reclosure can cause an increased overvoltage (voltage doubling) on the cable depending on the timing to re-energise the cable. To explore the worst condition, the resistance of the reactors should be small to increase the retained voltage and the timing of the re-energisation has to be adjusted to yield the greatest voltage step. The condition is examined for a range of fault timings and locations. The situation needs to be more carefully considered because the oscillations die away slowly. The maximum voltage seen between circuit breaker contacts at the time of reclosing is greatest in the 30% cable scenario but is still only 467kV, whereas the maximum reclosing voltage is greatest on the 60% scenario at 523kV. Both occurred when the cable is in the centre of the line. Both are well within SIWV.

LIGHTNING OVERVOLTAGE

The cable head voltage is worrying and it would be necessary to determine the touch and step voltages in the area of the buried cables.

This phenomenon relates to a situation in which the sheath of the cable is earthed at the transition tower along with the overhead line tower and overhead earth wires. It is assumed that a lightning impulse occurs on the overhead line earth wire close to the transition tower. The question is the lightning induced voltage on the cable sheath. The earth resistance value of 3ohms is assumed for the overhead line gantry and cable head. Each of the first 5 towers from the gantry was assumed to have a grounding resistance of 10ohms as was the earth of each cable joint.

The study showed that the grounding wire initially carries 75kA falling to zero in about 120µs. Lightning current in the grounding resistance of the gantry and cable head peaks after about 50µs with about 23kA whereas the cable's metallic sheath has about 2kA for over 300µs.

This results in cable head voltages of about 70kV peaking at 50µs after the strike. By 500m into the cable the voltage peaks at 30kV after 120µs from the fault, by 1km out it has fallen to 12kV peak after 175µs and by 2km the voltage is a slow wave peaking at about 250V. Particular care must be considered in the grounding resistance value of the OHL/UGC transition station in order to keep induced sheath overvoltages below 40-60 kV [IEC62067].