Fault Location Techniques for One of the World's Longest AC Interconnector Cables

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Abstract

The electrical distribution system on the Isle of Man is linked to the UK power system via a 90kV AC subsea interconnector cable. The total length of the interconnector is approximately 108 km of which about 104 km is subsea cable.

Because of the importance of this installation the Manx Electricity Authority requires a strategy to deal with any fault that may arise with this cable. In the event of a fault one of the first requirements would be to determine a reliable estimate of the actual fault location on which the remaining actions would then depend. It was found that the extremely long length of cable posed its own difficulties in this respect and that fault location equipment designed for much shorter cables routes would not be suitable. The Manx Electricity Authority therefore initiated a programme of work to build a theoretical model to predict the magnitude of the Time Domain Reflectometery, TDR pulse likely to be effective over the whole length of the cable and then carry out field trials of TDR measurements during a maintenance outage.

Using specialist pulse generators and a high-speed storage oscilloscope during this outage it was possible to locate the remote end and a known subsea joint at about 60km from the test point. The joint was located to within 150m of the position determined from the installation records, an accuracy of 0.14% of the total length.

1 Introduction

The electricity demand on the Isle of Man is provided for by the Islands diesel and gas turbine generators and a submarine interconnector cable which was commissioned in 2000.

The maximum demand on the Island is in the order of 90 MW. The submarine cable capacity is 50 MW. The two major benefits of the cable are spinning reserve allowing larger units of plant to be used, and access to the UK electricity trading market by which MEA can export or import power to optimise its economic operation.

The interconnector was laid between Bispham Substation near Blackpool and Lord Street Substation at Douglas in the Isle of Man. It consists of around 104 km of subsea cable which comprises three cores of XLPE insulated, lead sheathed, 300mm copper conductor cable laid up within a protective galvanised steel wire armour outer layer, with approximately 2km of land cables connecting to the substations at both ends.. The subsea section was manufactured to a nominal design by both Pirelli and BICC. The separate lengths being jointed, using a fully flexible joint design, into the single 104km length buried within the sea bed.

In the event of a fault the essential initial element is the identity of the fault location since the equipment needed to undertake repairs is dependent on whether the fault was in a land section, shallow water or the deeper main sections of the route. To aid in the development of the strategic plans the MEA initiated an investigation into fault location techniques suitable for very long cables.

An initial review of the available techniques and equipment was carried out with the assistance of Elmeridge Cable Services. This initial review concluded that Time Domain Reflectometery, TDR was the preferred method of generalised location prior to pin-pointing at the site location.

With the TDR system a very short pulse is sent down the cable. A portion of the pulse is reflected at points where there is a change of impedance, typically joints or a fault, along the cable and these reflections are captured and timed by the instrument. The distance from the sending end is then calculated from the 'time of flight' between the sending and the reflected pulses and the velocity of propagation of the cable.

It was considered that commercially available TDR test sets may not always be suitable because they could not deliver sufficient energy in the input pulse for the reflected pulse to be detected over such a long cable.

2 Specialist equipment

Commercially available TDRs combine the pulse generator, data capture, display and analysis components into a single unit with a straightforward user interface. To develop a TDR technique suitable for the Isle of Man Interconnector it was decided to revert to the basic principles of a TDR and use a separate pulse generator with the data being captured and analysed on an oscilloscope.

ERA has a pulse generator capable of delivering a 100 V square wave pulse with a duration of between 0.1 and 10µs. This pulse generator was supplied by IPEC Engineering as part of a Portable Transponder System that is used in conjunction with the OSM-Longshot PD Spot Testers and calibrated high frequency current transformers sensors to locate and quantify partial discharge sites along the length of a high voltage cable.

It was considered that this pulse generator together with a Lecroy WaveRunner 350MHz digital storage oscilloscope would form the basis of a TDR system that may be suitable for detecting faults in the Isle of Man interconnector.

To determine whether this equipment would be suitable the MEA decided on a 2 stage approach to the assessment. The first stage was to create an analytical model of the interconnector and determine the likely attenuation of an injected pulse. The second stage was to carry out a trial on the interconnector during an outage.

3 Analytical modelling

3.1 Approach

The primary objective of modelling was to investigate whether TDR testing could be used as a pre-location technique to detect faults along the interconnector. The work involved:

1) Conducting TDR tests on a length of cable available at ERA
2) Creating a model in ElectroMagnetic Transients Programme, EMTP, to compare the results with the waveforms generated by the TDR test
3) Creating an EMTP Model of the Manx Interconnector to determine the magnitude and duration of pulse required to detect the far end of the cable.

3.2 Initial tests

The IPEC pulse generator and LeCroy oscilloscope were used to conduct TDR trials on a 129 m length of 3-core 11kV Al/XLPE/PE cable available at ERA.

The attenuator was used to reduce the open-circuit amplitude of the pulse to about 65 V so that the input pulse and the reflected pulse could be viewed on the oscilloscope without having to 'scroll' the screen. Without the attenuator the open circuit voltage delivered by the pulse generator was approximately 140 V.

The test circuit is shown in Fig. 1

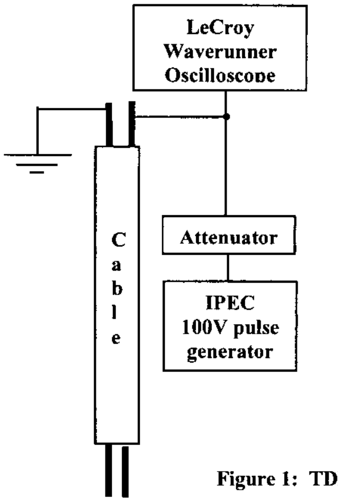

Figure 1: TDR test circuit

3.3 Modelling

The cable parameters used for the modelling were derived from measurements made on the cable sample. Because the sample cable did not have individual core screens the measured capacitance value was considered unreliable.

The initial EMTP models were set up using a distributed cable model. This model was not frequency dependent and did not give the degree of attenuation and rounding of the waveshape which was expected. It was considered that a frequency dependent cable model would better represent the phenomenon that was taking place. It was decided to use the Jmarti cable model in EMTP to represent the cable.

The test network for the 3-core cable was set up with the cable sheath unearthed. The TDR test was carried out between two conductors, with one conductor earthed. The EMTP calculation using the Jmarti cable model was first conducted with the measured 11kV cable parameters. The relative permittivity of the insulation was then increased by 50% to alter the capacitance of the cable model, confirming the effect of capacitance on the magnitude of the reflected wave.

The results for both calculations are compared with the measured values in Table 1.

Parameters	Measured Data	Jmarti Cable Model original ε	Jmarti Cable Model ε increased by 50%
Injected signal (V)	48.4	48.7	46.7
Reflected wave (V)	20.8	21.5	22.3

Table 1: EMTP calculation results for 11kV cable

An EMPT model was then constructed for the Isle of Man interconnector. The interconnector model included

- 1.94 km of land cable at the Bispham (UK) end, 104 km subsea cable in three sections and 1.75 km of land cable at the Lord Street (IOM) end.
- The land cables are single core Cu/XLPE and the subsea cable is three core Cu/XLPE. The subsea cable has a lead sheath around each core thus it was considered as three single-core cables.

The cable characteristics required for the model were derived from the cable data provided by Elmeridge Cable Services.

The model was run for pulse widths of 1 μs and 10 μs and the results are given in Table 2

Parameters	IOM Cable Model	
TDR Input Signal (μs)	1	10
Length (km)	108.69	108.69
Injected signal (V)	72.95	73
Flight time (ms)	1.287	1.289
Velocity of propagation (m/s)	168.9 x 10^6	168.6 x 10^6
Reflected wave (V)	0.096	1.5
Ratio of reflected wave w.r.t. injected	1 / 760	1 / 49

Table 2: Results for EMTP model of interconnector

From these results it was concluded that the reflected wave would be of a magnitude which is measurable using the LeCroy Waverunner oscilloscope. Thus it was decided to proceed with the second phase of the work, to carry out TDR trials on the actual interconnector.

4 Interconnector trials

4.1 Procedure

The equipment used for the TDR trials on the interconnector was the IPEC pulse generator and HTRE LeCroy oscilloscope that had been used for the initial tests at ERA. However it was recognised that subjecting the oscilloscope to a 100 V pulse with the oscilloscope amplifier set to mV/div may cause some difficulties. To overcome this IPEC designed and built a voltage divider and cut-off amplifier to chop the peaks off the signal received by the oscilloscope. The test set-up used in shown in figure 3.

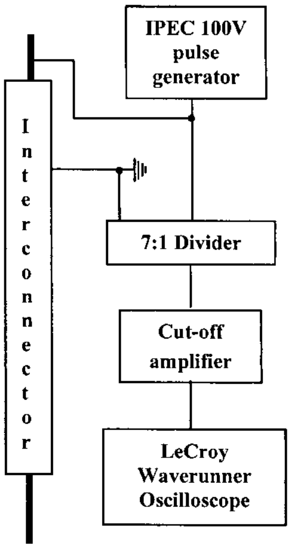

Figure 3: Interconnector test arrangement

The tests were carried out from the Blackpool end of the interconnector during a cable outage on 19th August 2005. The test connections were made to the interconnector cable sealing ends at Bispham Substation.

Tests were carried out on each of the 3 phases with the far end of the cable either open-circuit or earthed. Tests were carried out with pulse widths of 1 and 10 μs and with an amplifier and divider included in the measurement circuit for some tests.

4.2 Results

The first test with a 10 μs pulse revealed a reflection at about 1.2 ms. This was the expected time of flight for the far end of the cable. A test with the far end earthed showed a reflection with a reversed polarity which confirmed that the far end of the interconnector had been detected. See Figures 4 and 5.

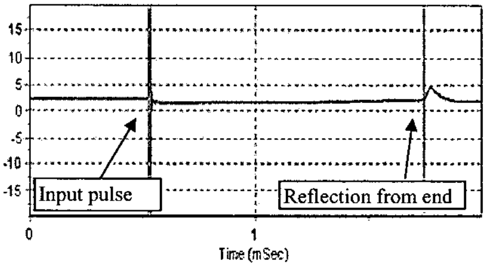

Figure 4: TDR trace, open circuit

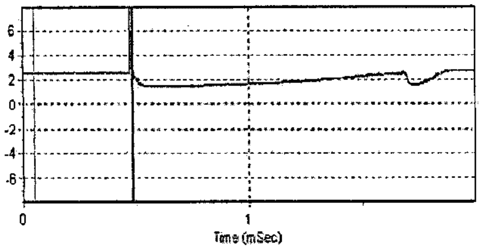

Figure 5: TDR trace, short circuit

In further tests it was found that by reducing the pulse width and using the IPEC voltage divider and amplifier, joints in the land cable could be seen together with the land/sea transition joint, and also a joint between the first BICC section of cable and the Pirelli section, Figure 6. Expanding a portion of the stored waveform allowed the position of the joints to be determined with greater accuracy, Figure 7.

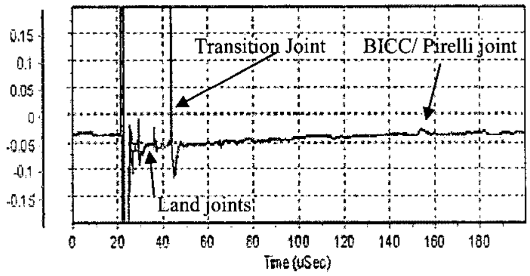

Figure 6: Details close to Bispham

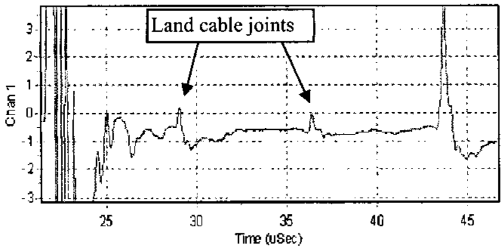

Figure 7: Expansion of trace

Further analysis of the reflection with a 1µS pulse width allowed the time of flight to be measured for the reflections from the joints in the land cable.

In one test a second reflection of the far end of the interconnector was identified together with the 'mid-point' 60 km joint between the Pirelli cable and the second section of BICC cable. The second reflection occurs when the reflected pulse is re-reflected at the sending end and continues to travel up and down the cable. For the second reflection of the far end to be seen the pulse and its reflections had travelled more than 400 km and had retained sufficient magnitude and definition to be identified on the oscilloscope, figure 8.

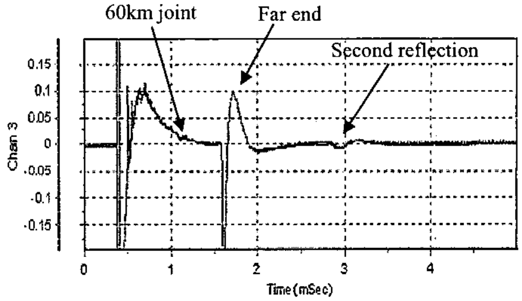

Figure 8: Mid-point joint and second reflection.

The downward sloping curve between the initial pulse and the first reflection of the far end is a function of the measuring equipment and could be removed by manipulation of the recorded data.

The time of flight for all of the features seen was recorded and used to calculate the cable length from the sending end to the features. The calculations were based on the known total length of the cable circuit. A detailed analysis of the calculated distance to the land joints was not carried out thus the results for these features are only approximate. The calculated distances are compared with the distances derived from the route records in Table 3.

		Length, m		
Feature	Time, µs	Calculated	From records	Difference
Start	0	0	0	0
Land joint	7.19	640	623	17
Land joint	14.72	1310	1270	40
Land/Subsea transition	21.6	1923	1940	-17
'10 km' BICC/ Pirelli Joint	131	11661	11508	153
'60 km' Pirelli/ BICC Joint	721	64178	64300	-122

Table 3: Position of 'features'

The expected time of flight to land/sea transition joint at Douglas was 1198 µs. The analysis of the traces that were recorded did not reveal any feature that could have been the land/sea transition at the Douglas end. This was to be expected as it would be a relatively small change of impedance at more than 100 km from the test position.

The measured total time of flight for the pulse to reach the end of the cable and be reflected back was 1.218 ms. This is in reasonable agreement with the time of 1.289 ms given by the model. The overall 'core' length for the circuit was calculated to be 108418 m, this included an allowance for the lay-length of the 3-core cable. The overall velocity of propagation, calculated from the core length and the time of flight was 178 m/μs as compared to 168.6 m/μs derived from the model.

5 Discussion

With the TDR technique a reflection is expected where there is a change of the characteristic impedance of the cable. The magnitude of the reflection seen will be a function of both the magnitude of the change of impedance and the distance to the feature. Also, if there are a number of features along the cable, part of the signal will be reflected at each feature, this will reduce the magnitude of the signal received at each subsequent feature.

It was noted that the reflections from the land cable joints are smaller than those from the land/sea transition joint. This is expected because the impedance change at the land joints is only that due to the joint whereas the impedance change at the transition joint is due to the difference between the land cable and the subsea cable.

The reflections from the two Pirelli/BICC joints are considered to be due to slight differences in design that affect the characteristic impedance of the two cables. The Pirelli cable is a fully insulated system i.e. the lead sheaths are oversheathed with a fully insulating MDPE jacket. The BICC cable, however, has a semi-conducting oversheathing material, the three lead sheaths are therefore in electrical contact with each other and the surrounding sea water. Also the three lead sheaths within the BICC cable were interconnected at about 25 %, 50 % and 75 % of the distance along the BICC cable.

The overall velocity of propagation calculated from the total time of flight and the total cable length is an average of that of each cable section. It is reasonable to expect that the velocity of propagation will be slightly different for each section of cable. The velocity of propagation for each section can be calculated from the time of flight between features and the appropriate core length from the route records. These values would then be used to determine a more accurate location for a fault, if one should occur in the future.

As with any use of a TDR for fault location it is essential that accurate route length and cable details are available if accurate results are to be expected. This is of particular importance where a circuit includes a number of different cables each having a different velocity of propagation.

6 Conclusions

The work that was carried out has confirmed that TDR techniques can detect the far end of the cable and other features along the length of the cable including a joint around 60 km from the sending end. The joint was located to within 150m of the position determined from the installation records, an accuracy of 0.14% of the total length.

The work has also provided a TDR 'fingerprint' for the cable which will assist in any future TDR fault location activity if a fault should occur.

It is anticipated that the 100 V, 10 μs, system used should be able to detect any change of impedance due to a fault. The change of impedance due to a fault is expected to be considerably greater than that due to a cable joint.

It should be noted that although TDR will provide a distance to the fault it is the length along the cable and as such will only be used as a pre-location tool. Other techniques would then be needed to accurately locate the fault before the cable was cut and lifted for repair.

The techniques currently being investigated include the use of the SG Brown TSS Cable Survey System to accurately determine the physical position of the fault on the power cable.

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