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FACULTY OF TECHNOLOGY
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ELECTRICAL ENGINEERING

MASTER'S THESIS

CHANNEL ESTIMATION AND ON-LINE DIAGNOSIS OF LV DISTRIBUTION CABLING

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Abstract

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Channel estimation and on-line diagnosis of LV distribution cabling

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Fault location is an important issue that has been investigated for many years. Referred to low voltages, distribution networks used to be always checked by operators using a wide range of methods, but due to their origin, it is usual to have a lot of active faults existing in the network but going unnoticed.

In this work an approximation to a novel system to locate faults on-line is proposed. It is based on a strong background about actual fault detection methods and in channel estimation of low voltage power lines with the presence of faults.

To check how novel techniques, which are facing noise and attenuation could locate faults in the distribution network, input impedance measures were taken to characterize the transmission line and compare the state of the channel through different faulty situations. It was proved how variations in the structure of the cable in a determinate point can be detected from impedance analysis, specifically water ingress under the sheath of low voltage cables.

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Lappeenranta, May 18, 2012

César Picos Hernández

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Abbreviations

AC	alternate current
ACR	auto-correlation
AMCMK	1 kV PVC insulated, PVC sheathed cable with sector shaped, stranded aluminium conductor
AMR	authomatic meter reading
AXMK	1 kV power cable with XLPE insulated aluminium conductor
CCR	cross-correlation
CENELEC	European committee for electrotechnical standardization
DC	direct current
DG	distributed generation
DSM	demand side management
EU	European union
FDR	frequency domain reflectometry
HD	harmonization document
HEMS	home energy management system
HV	high voltage
IDFT	inverse discrete Fourier transform
IFT	inverse Fourier transform
LV	low voltage
LVDN	low voltage distribution network
MV	medium voltage
OFDM	orthogonal frequency division multiplexing
PG	power grid
PLC	power line communications
PQ	power quality
PRBS	pseudo-random binary sequences
PVC	polyvinyl chloride
SDR	software-defined radio
SG	smart grid
SSTDR	spread spectrum time domain reflectometry

TDR	time domain reflectometry
TDT	time domain transmission
TEM	transverse electromagnetic
USRP	universal software radio peripheral
XLPE	cross-linked polyethylene

1 Introduction

1.1 Background

In developed countries, access to electricity for the population is a fact. Wherever you live, you can apply for energy services. A sign of the expansion of this in the developing countries is how 2012 was declared by the United Nations the "International Year of Sustainable Energy for All", in an attempt to raise the rate of people accessing energy in the next 18 years [1]. These aspirations are closely linked with the growth of new alternatives in the electricity market and the subsequent improvement in efficiency.

The link between the population and the energy sources is what is called the Power Grid. Nowadays the medium to supply the electricity to the customers is much more than a simple feeder. It is becoming in a bidirectional path where both energy and data exchange are playing an important role. The use and the integration of renewable generation sources in the grid is involving the necessity of bringing suitable interconnection mechanisms between the new innovative components of the grid and the traditional electricity grid. These mechanisms are included in the Smart Grid concept [2], where companies and customers turn into a synergy, and the management and the control of the network has to be boosted. So that is the point where the energy flow exchange needs to be relied on communications between the parts. Those communications require a channel, and part of the potential of the new model is based on taking advantage of the existing infrastructure to act as the backbone for data transmission.

An important part of this structure is composed by the distribution network, which is directly interacting with the customers, new active agents in the Smart Grid scheme. In the distribution network it can be considered also a subgroup which is not critical because of the amount of users' dependence but it is because of its size, the Low Voltage (LV) distribution grid. Referring the Energy Market Authority Annual Report to the European Commission in 2011, there were

235.901 km of low voltage distribution network in Finland at the end of 2010 [3]. The total length of the infrastructure is significantly increased if it is considered the complete distribution grid.

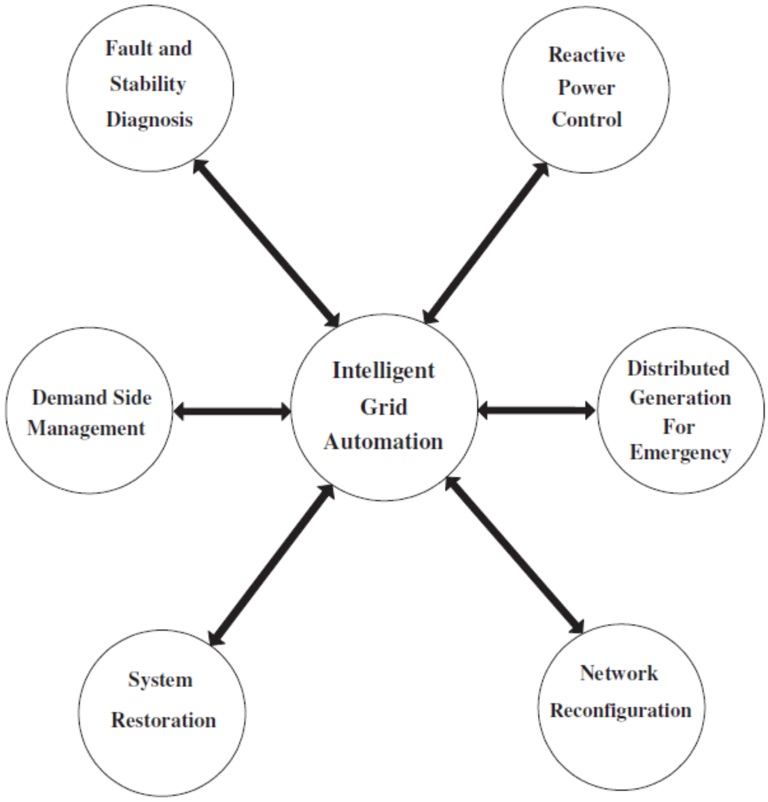


Fig. 1.1. Summary of the main elements to be consider in the SG design according to [2].

It is crucial to have a properly managed power network to avoid power outages, and fight harmful effects as the intermittency phenomenon and their consequences. All these factors are affecting to the power quality (PQ), which is an indicator of the service delivered to the customers, and has its importance in regulations and therefore, in companies policy [4]. The tool used by the Smart Grid to face the communications is the Power Line Communications technology, taking the role of its main data delivery system and, consequently, allowing management and control of the power lines. And it is done taking advantage of an already existing network, with its advantages in coverage and reduced deployment costs.

PLC is also being used in the transmission side of the grid but the principal development guidelines are expected in the distribution side. Some applications regarding the LV distribution network control are the automatic meter reading (AMR), demand-side management (DSM), vehicle-to-grid communications or home energy management system (HEMS) [5], each of them closely dependent on PLC reliability.

As is pointed out in [5], PLC can also take part in the detection of malfunctions in the grid in order to maintain the PQ of the system. When there are breakdowns related to grid devices is easy to locate and access them to repair the fault. But it does not happen when the faults are on the grid power lines, because of the obstacle about their operation in uncontrolled environments and subsequent detection and localization costs. Furthermore, the LV side has many areas where the installation is underground, thus limiting possibilities of immediately response to rising faults. This is one of the reasons for the huge efforts put in the fault location process and its automation, trying to turn that work in something easier, and above all, faster to reduce the non-availability of the system.

The European Commission, under the European Electricity Grid Initiative, has released a package of targets for the next years known as the EU's 20-20-20 targets. These measures are related to improve grid efficiency, considering the new energy sources. As its pointed in the "SmartGrids Strategic Research Agenda 2035" there are many topics to be boosted in order to achieve the proposed targets, and some of the multiple researching paths are linked to how identify and locate faults in the grid [6].

There are many detection and location techniques available for high and medium voltage fault location [7][8], and now there is a growing research area in low voltage distribution network (LVDN) fault location.

1.2 Objectives

Understanding the requests for efficiency improvements in the grid in terms of promoting Smart Grid capabilities, it is assumed that many efforts have to be done to maintain and control the availability of the system. It is important for the companies to know when its infrastructure has some unforeseeable problems that may affect service quality, and with that, on Smart Grid performance.

The main purpose of this study is the evaluation of fault location techniques capabilities in terms of their scope for low voltage distribution grids. It is implying characterization and estimation of the communications channel, identifying its suitability to perform on-line monitoring which allows the recognition of changes in the state of the channel. This is, try to detect faults in the lines before they will become permanent.

In this way it is important to know which frequency has to be used in the detection process. In this document a survey about the fault location process, contemplating high frequencies in terms of the LVDN, is made.

There are several issues to know attempting to understand the behaviour of low voltage systems. One of the most important is the multipath effect due to their multiple-branches configuration. Furthermore it has to be noted that considering the continuous switching process of loads in the network, they are showing time-dependent behaviour.

With a previous study of how the LVDN are, and how the fault location and detection mechanisms work, a practical approach to the channel model will be analysed.

1.3 Outline of the project

The Section 2 is a brief survey about LVDN, how they are, which type of cables are employed and the introduction to a novel distribution system using DC, and which is boosting the capabilities of the Smart Grid concept.

The Section 3 is focused in the analysis of actual fault location and detection techniques, reviewing how fault are being located in the low voltage side of the distribution network.

In Section 4 a theoretical study on transmission lines behaviour and power line channel characteristics is performed. In this chapter, they are explained also some basics about fault location.

The Section 5 an analysis about on-line monitoring and fault location of actual and possible future implementations is presented.

Finally, in Section 6 an exhaustive measurements campaign is shown in order to characterize the low voltage power line channel in the presence of faults and check its suitability to apply that previous on-line diagnosis system. Different scenarios are presented with this purpose, simulating faults in real systems and measuring the channel for single cable segments, and a simple branched scheme.

The Section 7 contains the main conclusions of this work and some future considerations which have to be taken into account.

2 Low Voltage distribution characteristics

2.1 Low Voltage systems overview

The low voltage side of the power grid is the nexus between the transmission system, where the main power lines are, and the customers. They consist in many substations where there are a transformer and the lines taking the power to every customer in the grid. In those primary substations in the distribution scheme are the step-down transformers to take power from the higher voltage side of the network, and reduce it to a suitable value for local distribution. It is done in traditional distribution networks by transferring power to different AC levels. There are also the mechanisms to interconnect every branch outgoing towards customers, represented by bus bars. In these bus bars every branch feeder is placed with the corresponding protection and switching components.

From the communications point of view, some physical limitations exist regarding transmission speed and distance reach, as it is studied in [9]. The presence of strong interference sources causing impedance fluctuations and the attenuation are two of the main problems faced in this power line channels.

Distances covered in traditional local area distribution networks 400VAC are usually up to 1 km long [10]. This is one of the main limitations in terms of attenuation, but not the only one. According to the study carried out in [12] for MV channels, if the number of branches is increased, it affects to the system introducing attenuation and distortion. If it is moved to a LV grid, the effect of the branches will be also noticeable as it is presented in [13]. In addition, to the power absorption due to each one of the branches, which affects to the attenuation, it has to be taken into account the presence of multiple reflections. Those reflections grow at the same time that the number of branches is increased.

Regarding to transmission reliability point of view and as it can be seen in [14], with a growing number of branches it is also associated the need of increase the transmission power to allow communications.

The impedance effect of the loads is another harmful effect in terms of communications performance, regarding to attenuation problems [15], but also keeping in mind the reflections caused by the mismatches and the associated distortion. The mismatches in a communications channel rise when loads impedance is different from the line characteristic impedance. Usually different elements with impedance matching purposes can be used in transmission systems. The problem is that the impedance matching cannot be achieved easily (it is not economically justified) or simply those matching mechanisms do not exist.

2.2 The LVDC distribution system

As it is pointed in [16], distribution systems have to face the new challenge of small-scale distribution generation and the presence now of a two-way power flow in power lines. The low voltage DC distribution system is a novel concept where 20/1/0.4 kV, or more simplified 20/1 kV transformers are now making the AC/DC conversion near MV lines. The DC/AC conversion, traditionally placed in secondary substations (Fig. 2.1), is made at the customers' side. It is replacing usual 20/0.4 kV AC systems in areas with distributed population such rural areas.

The maximum allowed voltage in the LVD 73/23/EEC standard in underground cablings is 1500 VDC. And this can be applied in the LVDC system by using a bipolar system with arrangement of three levels ±750 VDC and 0 V. The AXMK cable is one suitable and used cable type in bipolar LVDC system. AXMK cable has four conductors, and thus bipolar LVDC power distribution is provided with the arrangement of conductor for +750 and -750 VDC and two neutral (N) conductors short-circuited [10] as it is presented in Fig. 2.2. Benefits of this bipolar system are included in [11]. They are related with its higher transmission capacity due to the voltage difference between poles, causing the possibility of using smaller cable sections and reducing the number of LV transformers. Moreover, smaller power losses can be obtained under the condition of using the same cable sizes than those which are utilized in the traditional distribution system. There is also the possibility to arrange this system using a unipolar implementation, where connections are made to one voltage level.

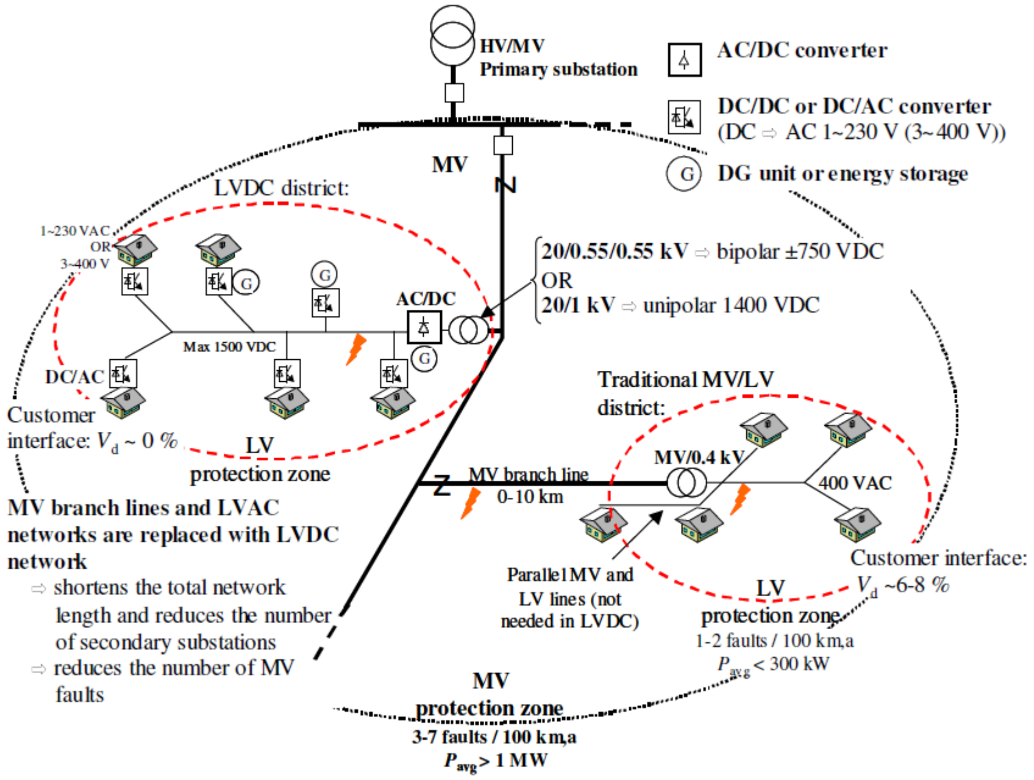


Fig. 2.1. LVDC distribution as part of traditional AC distribution network [17].

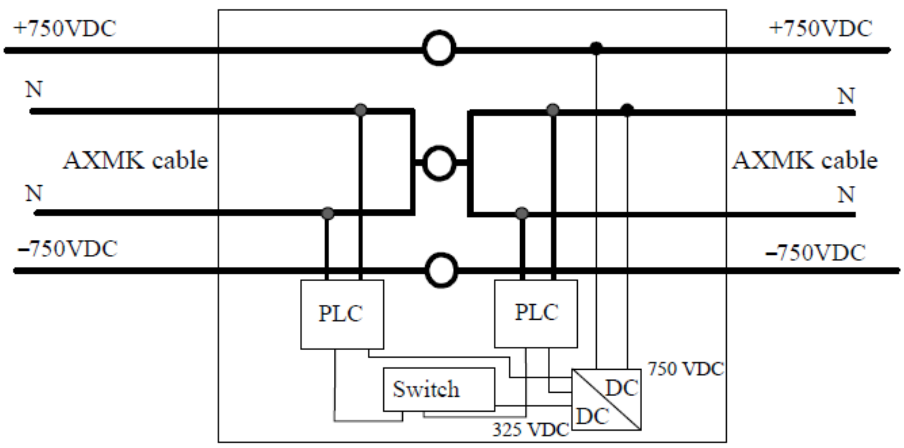


Fig. 2.2. Over-ground cable connection cabinet content for bipolar LVDC system as is shown in [10].

The increment of the transmission capacity and that transformers reduction implies directly the reduction of the MV network and the improvement in the PQ served to the customers [18], [19].

The increasing presence of power electronic devices, the call for more efficiency in the distribution of the electricity and the introduction of new schemes for the DG are putting the LVDC system in a privileged position as an innovative solution to cover all the proposed aims.

But there is not a simplification of the network with the new concept. Now the flow between the customer and the grid has fewer restrictions knowing that there is a bidirectional path for the DC. But it is implying to add new devices at the user end. And it is implying also to adapt the system to the current protection devices, and also to take care about the faults, which could be increased due to the increased complexity [19].

2.3 Cabling in LV

There are many different options in the actual market regarding which cables to use in LV networks deployment. The efforts of this concrete study are focused in underground cables. Some advantages using them are lower maintenance costs or less exposure to weather conditions, but it has to be taken into account their more expensive installation process.

As it is said in [20], the selection of one cable type must be done starting from the latest manufacturers catalogues, and being aware of its concrete application. In this document, two different types of cables have been studied, attending to their actual usage in distribution LV networks in Finland with nominal voltage 0.6/1 kV. The required study of the power line channel give the key to use similar cables to those which are been used actually in real distribution scenarios. It is also interesting to see, because of its role in fault location, their relation with the attenuation. And this attenuation parameter is straight related with the insulation material which is covering the cable cores.

Inherent to cable properties, two different insulation materials have been chosen to perform the analysis: PVC and XLPE, both widely extended in actual LV distribution systems. Main characteristics of the two selections made for the study are presented in the following points.

2.3.1 AXMK cables

The AXMK cable consists of four aluminium conductors with a Cross-linked polyethylene (XLPE) insulation and a lead-free polyvinyl chloride (PVC) sheath [21]. In LV networks, which means the presence of low stresses is important the cable insulation's dielectric constant values. The XLPE insulation holds little charge causing low losses, which is characteristic of good insulation materials [22].

2.3.2 AMCMK cables

The AMCMK cable has three-sector shaped aluminium conductors and an additional protective earth conductor wrapping them and made with a concentric copper wire layer. It also has both PVC insulation and an outer sheath. The cores are identified by colours following the HD 308 standard [23].

2.3.3 Physical and electrical characteristics

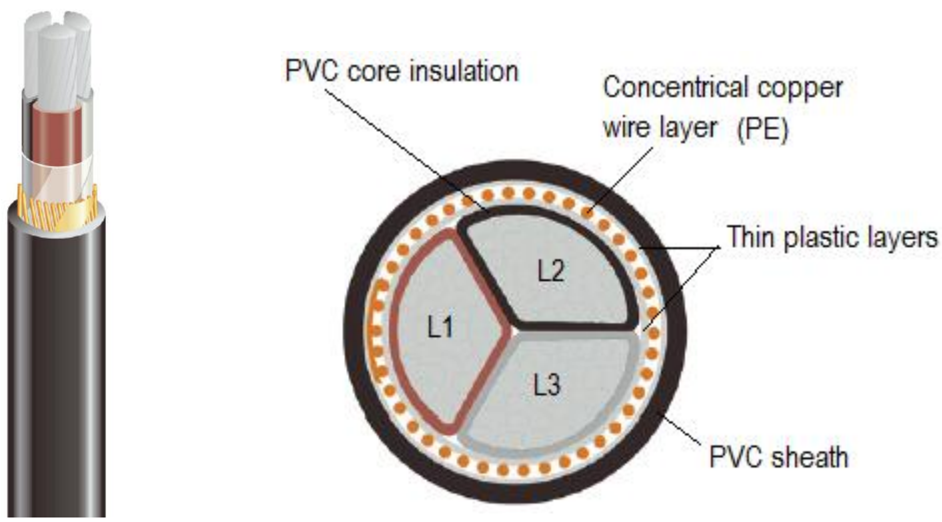


Fig. 2.3. AMCMK structure, cross section and conductors' identification [24].

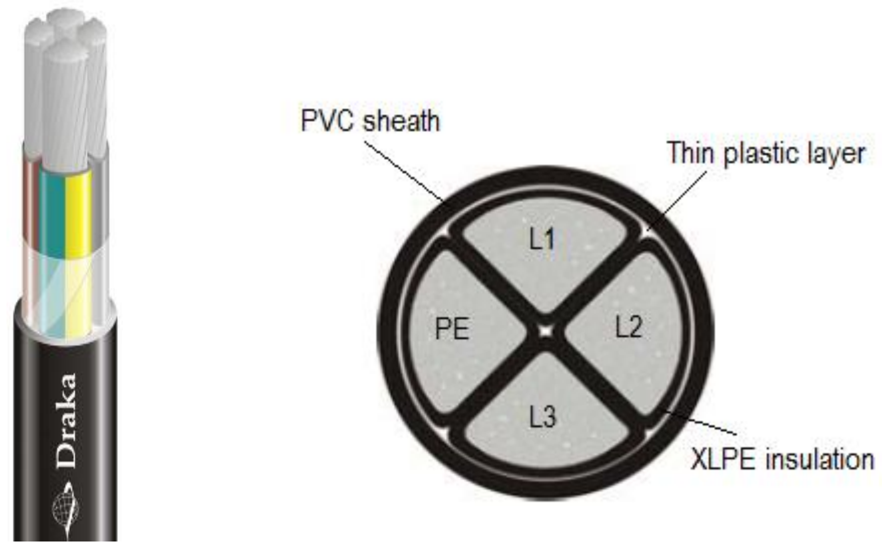


Fig. 2.4. AXMK structure, cross section and conductors' identification [21].

Following Fig. 2.3 and Fig. 2.4, in the AMCMK can be seen the 16 mm cable's section with each of the three conductors, and four conductors in the AXMK case. In both cables there is a thin plastic film under the sheath, protecting cables from moisture and other external substances.

Tables below show some interesting structural values about these cables composition and also their operating electrical characteristics per unit length.

Table 2.1. Physical characteristics of the cables.

Cable Type	**Cores**	**Conductor cross-section [mm²]**	**Insulation**	**Outer sheath**	**Average thickness [mm]**	
					sheath	**insulation**
AXMK	4	16	XLPE (chemical)	PVC	1.8	0.7
AMCMK	3	16	PVC	PVC	1.8	1

Table 2.2. Electrical characteristics of the cables.

Cable Type	**DC Resistance of phase conductor [Ω/km]**	**Operating Capacitance per core [pF/m]**	**Operating Inductance per core [nH/m]**
AXMK	1.91	100	230
AMCMK	1.91	300	300

2.3.4 Joints

Joints are another element making the LV distribution grid. Due to its branched structure, multiple joints could be present from one substation to different customer ends. They can be in cabinets in some cases or buried as the rest of the cable length.

The connections between the cable segments and the joints can be done directly by crimping or by bolting. In this case, avoid moisture ingress or other protection mechanism typical in jointing are no required because they will be in a controlled environment. Aluminium locks are used in each cable end, attached to the cable by hexagonal compression which implies avoid soldered connections. Between each core and the locks a low resistance connection is made with the adequate grip [25].

Joints have an important influence in the communication channel, because they are introducing a certain degree of mismatching in the power lines. Also branches can be seen as points where the power is absorbed, causing notches in the gain transfer function. An increasing number of joints are increasing the number of mismatches, causing losses in the system.

3 Cable fault detection and location

3.1 Background of Cable Fault Location

Fault location in the power grid is closely connected to electricity distribution networks growth and continuous improvements. Recognizing faults and avoid their effects are key issues when one of the system quality parameters such as availability comes into a mind.

For many years, rudimentary actions, such as the cable progressive cutting based on "divide and conquer" algorithm to detect the fault location were used. During a long period after that many technical advances were made in this field in order to reduce costs and make shorter the availability interruptions of the system. An analysis of faults and location methods from few decades ago presented in [26] give some practical example tests to be performed in different scenarios.

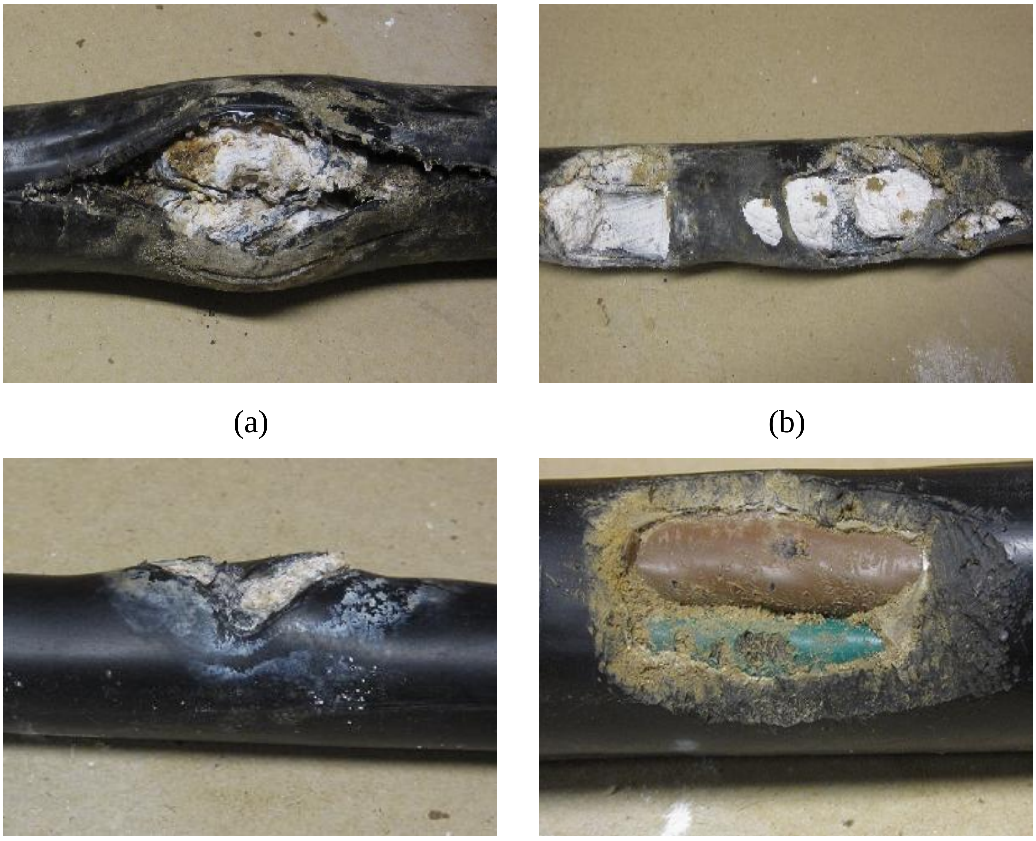
However, it has to be taken into account that the final purpose of this study is to know how faults in the distribution system are compromising power transmission capabilities. This requires a channel characterization in order to understand the behaviour of the system, but not only in its normal state but also when its state is influenced for some perturbation. A faulty condition in the system will be affecting to its performance, and therefore, its transmission channel state.

For this reason, a complete survey has to be made attending to how faults are, how they appear in the power lines. It is also interesting to know if it is possible to identify different channel states corresponding with different faulty stages.

3.2 Cable failure types

When there is a fault in one power line, usually it is caused by different external aggressions, changing the normal structure of the cable and affecting its behaviour. Those aggressions can be caused by a vast range of factors such as, amongst others, bad weather conditions, incorrect manipulation, working machinery without the knowledge of the cables' existence in a working area or animals. The two last faults cited sources are very common for underground cables in the post-installation process, if manipulation or some errors when the cables are being placed have not damage the cable before.

In this work, few samples of replaced cables due to a faulty state have been collected from an electricity distribution network company in Finland. They are the result of different incidents reported by their maintenance tools and operators. Most part of the cases are corresponding with final faulty states, where cables are already broken and the lines are not giving service anymore.



(a) (b) (c) (d)

Fig. 3.1. Real-case faults. (a) Totally damaged phase in LV cable, damaged by the incorrect manipulation during the plugging process at the installation (b) One phase totally damaged, aluminium oxide broke the sheath (c) Phase damaged by a screw, two different cuttings (d) Power cable gnawed by a mole, but still working. Replaced to avoid a future fault as this seen in (b).

Different types of faults can appear depending of the phases involved and the consequences of changes in the damaged cable's structure. The description of the different fault types is done in [27]. These are some explanations and comments about them, moved to the LV context:

- Contact fault: There is enough damage in the insulation that a connection appears between two or more cores. The most critical situation is when there is a short circuit between cores. In an energized cable the result can be an overcurrent and its related outcomes.
- Ground contact fault: Fault when one appears an unwanted connection between a conductor and the mass of earth. Note that again it has to be a lack of insulation in one phase, being the rest of them enough isolated to avoid mutual connections and appearing leaking currents from the faulty phase, which will be following the mass of earth path.
- Break: Damage in conductors, which can be a little gap in the core or a complete cut, creating an open-circuit situation. This fault sign will be compromising the availability of the power line if the impedance is high enough.
- Ingress of moisture: Very delicate process because of the moisture's tendency to spread along the cable. It has to be enough damage in the sheath and the plastic film protecting the phases in the cable to allow the ingress of moisture. The spreading process over the cable cannot be defined beforehand because it depends of the quantity of moisture penetrating and the cable's position. If there is some additional damage in the cores' insulation it can derive in one of the two first types of faults.
- Transitory: They used to be in LV networks. A typical scenario is a blown fuse, the replacement of the fuse and a normal performance of the system again. This means one of the most important characteristics of faults in the distribution networks: the coexistence during long periods with a normal behaviour of the system. The problem is when that fault harmful effects are rising more often. This is not a fault itself but a direct

effect of those core-to-core or core-to-ground faults, which can be producing arcing and voltage distortion.

Flashing faults or partial discharges, even when they can be appearing also in LV cables, is quite rare and they used to rise in the HV or MV sides. Despite that, there are studies as in [28] about how arcing and other transient effects can be detected based in current measurements but considering mainly, in this case, LV overhead lines. In [29], the possibility of rising arcing faults is linked to lines insulation deterioration and its combination with some specific environments as those where there is melting snow being filtered and mixed with salt or other impurities. That study considers three different methodologies for lines study regarding in which domain is the analysis done, such time, frequency, and time-frequency combination are. It is an example of how fault location methodologies are working, trying to find the best analysis option depending on the network state, accessibility or configuration.

3.3 Fault location in LV systems

3.3.1 LV Faults

One of the main characteristics of LV faults has already been described in the previous section. It is how faulty cables are working normally during long time even when they are damaged. This does not happen with higher voltages, where the stress conditions accelerate the damaging process.

As it is pointed out in [27], another problem in LVDN is how the power lines are permanently loaded, increasing the difficulty of their evaluation. The next challenge is how those loads are continuously changing, making a non-stationary environment. The continuous load switching process in the network, by devices switched on to and off from the network, is why power lines are not invariant scenarios.

3.3.2 Fault stages

In [30], there is an explanation of a *four-stage evolutionary* model of the fault state concerning its capability to affect the performance of the system, as it can be seen in the next four points:

- Dormant: The sheath and the protection have been damaged and there is not a complete protection avoiding the entrance of impurities. Line performance can be subject to the quantity and composition of any foreign component coming into the cable, but any fault indication rise. The cable is damaged but there are no signs of that.
- Incipient: It is one step over the dormant stage. Regarding that, a fault indication can rise for a short time, and then become again in a normal state. Faults can appear as transients or voltage disturbances, but it is easy to go unnoticed. Now, changes in line structure are more noticeable than in the first stage.
- Intermittent: The fault can be noticed by the rupture of fuses. There are transients or harmonics, which rise in a specific time interval and then the line can operate again in a normal state. A normal state means no fuses blowing but the fault still exists due to the actual differences of the line with the original one, and the probabilities to rise again are more than in previous stages.
- Permanent: In this stage there is no option to regress to a previous state. Fault, by becoming a short circuit or an open circuit is causing an interruption of the service. It is always an unwanted state, but even today is the unique stage that it is taken into account for repairing a line. Previous fault states are solved replacing blown fuses and leaving lines working again while its state is not permanent. This interpretation has the risk of an increase of the costs associated with many repetitions of the situation.

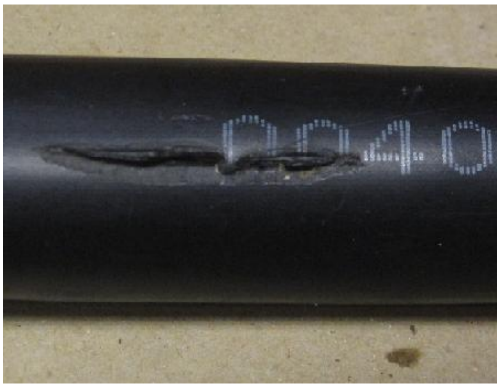


Fig. 3.2. Beginning of a fault with a cut in the sheath.

It is important to know about these stages when an on-line monitoring method is being proposed, to take advance of network's knowledge and avoid situations where an outage cannot be avoided and for sure losses will be affecting quality of service. For these reason the three first stages are the most interesting, and specifically the dormant and the incipient, where the fault is starting its rising process but there were not impact yet on the electricity distribution system availability. Fig. 3.2 can be an example of these states, with damage on cable's sheath but still intact conductors.

Even if an on-line monitoring of the faults is implemented in any area where the ratio of customers is not enough to consider outages costs, it is important to keep a certain knowledge of the network status. This knowledge can help on internal decision-making processes in companies. For example, about which parts of the distribution network can compromise the efficiency in the future or which of them may have priority to be replaced.

3.4 State of the art

The next fault location methodologies are some of the methods that have been used for a long time in LV distribution faults treatment. Practically all of them are implemented in the existing AC networks. However, most of those methods can be applied also in DC distribution networks. In this document the focus is in some of those, especially in methods in pulse echo measurements, because of their capabilities to detect impedance mismatches with a certain degree of accuracy. There are also some improvements, which are trying to face the attenuation problem using new techniques that are taking advantage of signal analysis. It has to be noted that operators used to apply different combinations of methods on the different stages of the fault location process (diagnosis, pin-pointing, confirmation), above all in the second half of the 20th century [27]. It is valid today, but efficiency requirements and technical advances are causing a convergence to simplify those stages. It will be done easier with higher accuracies allowing diagnosis and confirmation processes becoming closer.

3.4.1 Pulse Echo / Time-Domain Reflectometry

The time-domain reflectometry (TDR) methods are used in a big range of scenarios, particularly in the pre-location of faults, because it is a good approach to the fault characterization when the scenario has low voltage and low impedance. They are linked to the pulse echo based analysis, where an impulse is introduced in the network, traveling along the cable and the effect of the fault is seen in the reflected wave arriving back to the TDR device.

It should has a compromise solution regards to the accuracy to be reached. When the width of the pulse inserted in the cable is low, a narrow pulse, then the accuracy could be acceptable, but the attenuation will be high. So the analysis can only be suitable for short distances. If it is a broad pulse (long duration), then the results in longer cables can be seen but the accuracy could not be enough.

There is also a combination of TDR with adaptive filtering, trying to avoid requirements of operator’s skills for data interpretation. In [31], an algorithm is explained following this mixture, with an intelligent processing of the reflected signal obtained through TDR to seek the fault. This is a very interesting point of view because the intelligent processing of the current line state is taking into account the original state through a stored characterisation of the cable. Thus it can compare both states and process how is the error source.

3.4.2 Frequency and Frequency-Time-Domain Reflectometry

Frequency domain reflectometry (FDR) operates in a similar way than pulse echo or time-domain techniques, but taking advantage of the frequency domain. The main advantage of that is the use of multiple pulses, making a frequency sweep which is evaluating a certain range of frequencies. It implies more information about the line state because it is examining how the cable is from different paths. On purpose of complexity, it is increased compared with TDR technologies. This is the reason why TDR devices are more utilized for measurements, which do not require lines working on very high frequencies, covering short distances with enough accuracy.

But there is also a combination of both methods, as explained for example in [32] where an accuracy improvement is shown. The improvement in accuracy is related to detect the fault with less error rates and also to identify multiple faults and their type. Its operation mode is based on the use of a time-frequency cross correlation algorithm, which is related with the new techniques in the fault location field.

3.4.3 Transient Methods

Transient methods follow the same philosophy than the Pulse Echo/TDR techniques, but in this case, once the measurements have been taken before and after the re-energizing process, the results are automatically compared using the obtained curves.

3.4.4 Impulse Current method

It is a transient method that keeps all the advantages of the pulse echo methods. Obtained results interpretation can be easier for operators than for previous methodologies. The received impulse has the same polarity as the transmitted one, becoming the examined step produced by the fault more noticeable [33].
There can be a variable number of transients coexisting in the cable, due to the impulse flowing or the arcs produced by the fault in this method [27].

3.5 New challenges

3.5.1 SSTDR (Spread Spectrum TDR)

There is a modification in the classical TDR method using the spread spectrum technique to detect changes in impedance even in high noise environments, such as power lines. With this method, the problems associated in TDR with the distance and the resolution are tried to be solved.

A spread spectrum signal is injected now into the cable and when the signal is reflected in a mismatch, the received signal is correlated with the sent signal to compare the differences.

SSTDR has been tested in noisy environments, such as a simulated aircraft in flight successfully [34], but considering lossless cables. In such environment the test can be performed in a continuous mode, allowing the detection of intermittent failures. The main disadvantage is the dependence with the level of Signal-to-Noise Ratio received, which determines the correlation results.

3.5.2 Correlation pulse echo techniques: Pseudo-Random Binary Sequences

As a new alternative to the TDR techniques, a novel correlation pulse echo methodology using pseudo-random binary sequences has been developed [35]. The main purpose using this technique is the clear identification of the fault position through a well-defined signature, identifying the reflected pulse, which can prevail with regard to the noise present in the communications channel. This signature is based in the high cross-correlation levels that can be reached between a PRBS injected in the cable and the reflected sequence in a mismatch that occurs due to a fault.

One of the problems suffered by narrow pulses when they are injected into a cable with the traditional TDR methods is the attenuation in long distances. To partially solve this, wider pulses can be used, but by doing this, the accuracy of the location process decreases. With this new method the operation distance can be improved.

It has to be taken into account that the PRBS stimulus introduced in the line has no to be interpreted through the evaluation of the sequence by itself but through its own correlation. This correlation is made with the sent sequence (autocorrelation, ACR) and with the reflected sequence from the fault (cross-correlation CCR), obtaining clearly defined peaks result of existing mismatches. Then, they can be compared to measure the delay between them. The obtained delay is the value, which provides the estimation of the distance where the fault has to be located, using line's velocity of propagation.

4 Channel estimation

Channel estimation in PLC involves an important effort evaluating the range of frequencies suitable for communications, and how channel's statistical behaviour is changing. It is of special interest in broadband PLC because of their wider spectrum occupied. They are mostly based in Orthogonal Frequency Division Multiplexing, a multiple carrier digital encoding method widely used in wireless communications because of its capacity of adaptation to different channel conditions and its high spectral efficiency, amongst other capabilities to face multipath environments. This efficiency is reach overlapping subcarriers and making them orthogonal. Furthermore, lengthen the symbol period in each sub-channel in OFDM systems allows to reduce the Inter-Symbol Interferences (ISI). Furthermore, the orthogonally between sub-carriers theoretically allows to eliminate the Inter-Channel Interferences (ICI) [36]. This technical election takes sense looking PLC channels characteristics.

These channels characterization has been a sensitive field of study, since the potential of PLC to be exploited in the grid started its rising. There are multiple studies about how to model power lines for increasing communications reliability, because a better knowledge of the signal path is the main point to choose the appropriate techniques to optimize communication systems. Some examples of estimation techniques, as one-parameter deterministic model [37], blind channel estimation [38], wavelet-based [39], multipath study through GEESE algorithm [40], or the use of competitive neural network [41], are appearing in the last years to improve the knowledge of the network. And one of the most important properties for them is their adaptive character to be in concordance with every channel state in time.

4.1 Time-variant channel

As it was pointed in previous chapters, power lines are time-dependent knowing how channel is changing due to loads presence in the network and the switching effect. For this reason, evaluating the impedance characteristics of the channel in low-voltage distribution systems is a non-trivial issue because of the amount of loads present in the grid and those continuous variations typical of time-variant systems.

Simplifying, if only one load is present, for example evaluating a load at the end of one segment branch, channel's behaviour is depending of this load impedance. When its impedance is higher than the characteristic impedance of the line, the attenuation tends to be improved but the distortion increases. The same effect is seen when the impedance is decreased [13]. But in a multiple-branches scheme it should be noted that the characteristic impedance of the channel is a function of all the characteristic impedances of the elements being part of the system. Analysis by different loads groups is presented in [42], being an example of the environment's complexity, which is turning impedance measurements in a complicate process.

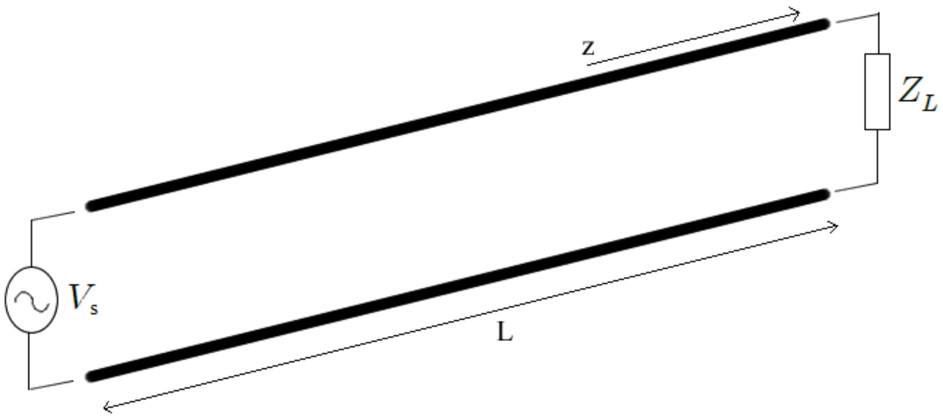
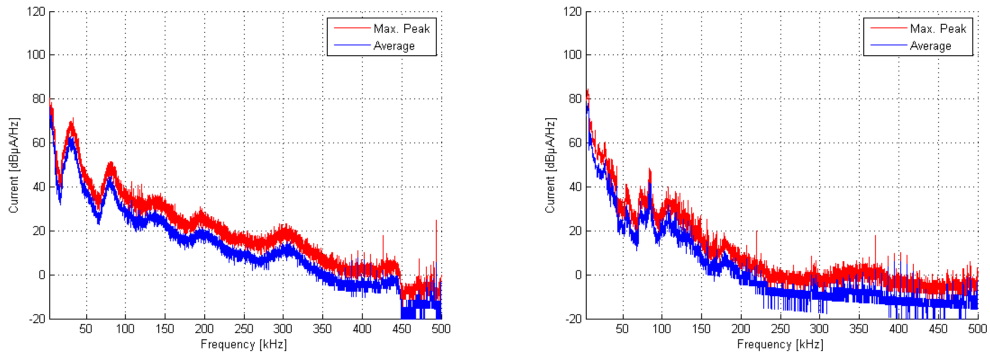


Fig. 4.1. Transmission line scheme. with the source and the load. When there is an open circuit, and when there is a short circuit at load's end.

A range of impedances could be used to identify every load effect on channel characteristics. The first and the last one in the range are always the impedance values corresponding to a short circuit and an open circuit. The medium term impedances are corresponding to low and high resistive loads. If these concepts are moved to the fault location idea, the fault can be seen such a mismatch according to those impedance values. As a last resort, this is the main idea of the fault identification, beyond the initial impedance identification of the channel or the continuous variations due to the loads. Then, for transmission reliability purposes the end of the branches may be matched with the load placed there, but for the fault identification point of view a well-defined load is easy to be interpreted when pulse echo techniques are being used.

4.2 Power line channel analysis at higher frequencies

Variations in time-domain are translated in an increasing selectivity in the frequency domain. This selectivity is caused by the attenuation presented by the transfer function, which is penalizing certain frequencies in form of notches making the signal disappear partially in these frequencies. That is the reason why they are called fading channels.



(a) (b)

Fig. 4.2. Examples of background noise up to 500 kHz with narrow-band PLC modems connected (a) and more disturbances sources added to the network (b).

The introduction of elements in the grid which are presenting non-linear loads and contributing with harmonic distortion, such as compact fluorescent lamps (CFL), is increasing the level of noise in the PLC channel. The study presented in [43] shows how this noise affects to the communications and how multiple correction and frames control mechanisms have to be enhanced in order to reach a reasonable communications quality in the actual CENELEC-A band for PLC.

A complete characterization about LV distribution is made in [44]. Differentiating indoor/public distribution with the industrial environment, some values as the input impedance, the signal attenuation, noise or group delay, are referenced regarding their frequency dependence. There are lots of mentions about the model presented by [45], where the channel is taking into account the multipath character of a complex network. These multiple-paths have a special importance in fault location, and chiefly on pulse echo techniques explained in the previous chapter. Those pulses will be affected by the network structure, conditioning channel's state, and a fault can be considered an undesired new member of the networks' structure. In the next chapter, following guidelines presented in [44], a transmission lines study, and particularly for LV lines is made.

4.3 Characterization of real cables used in LV systems

4.3.1 Transmission line theory

Transmission lines are physical medium guiding electromagnetic waves, or in other words, fluctuating electric and magnetic fields. Starting from Maxwell's equations, the basics to find the propagation modes that are characterizing that medium can be taken. When there are two conductors forming the line, separated by a dielectric, there is a potential difference, which allows at least waves propagate in the TEM mode. This mode is the principal wave in transmission lines and has both magnetic and electric field perpendicular to the direction of propagation.

Wave equations for voltage and current in frequency domain converted from the partial differential equations in time domain can be obtained using the dependence:

(1)

(2)

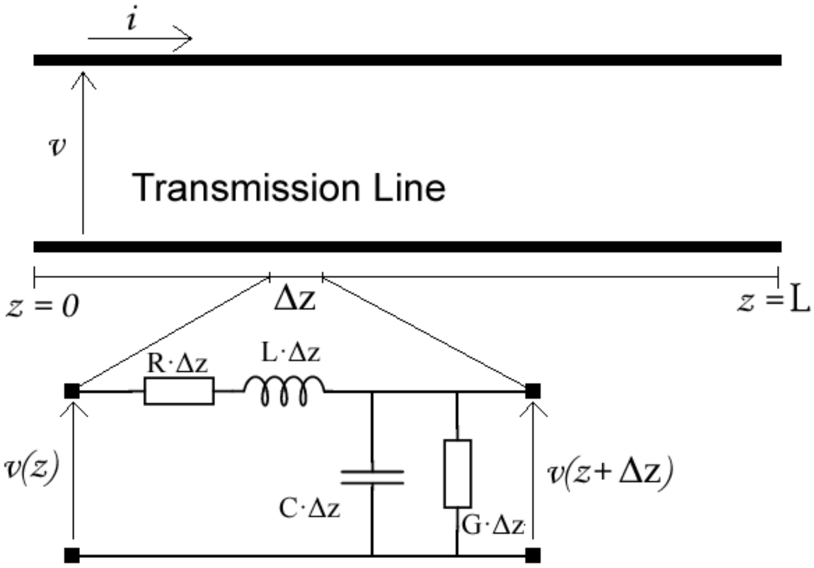


Fig. 4.3. Equivalent circuit for a discretization of the line with Δz.

Both differentials equations in (1) and (2) are depending on the primary parameters R (resistance), L (inductance), G (conductance) and C (capacitance) of the line along the *z* axis. From those, wave equations are:

(3)

(4)

Considering the general solutions of (3) and (4), these are the equations describing voltage and current:

(5)

(6)

The characteristic impedance of the line is represented by , whereas γ represents the propagation constant and both are defined as:

(7)

(8)

Characteristic impedance's phase is represented by . Angular frequency has the following definition:

(9)

The α and β parameters are the attenuation coefficient and the phase coefficient respectively, and they can be obtained using the circuital parameters of the line as is shown in (10) and (11).

(10)

(11)

Lossless line

If the primary parameters R and G are and , there is a simplification of (7), having then:

(12)

(13)

So, in this case the characteristic impedance will be real and the propagation constant will be pure imaginary, that is, there is no attenuation. It means that the current and voltage waves are in phase, and that the time-domain maximums of both curves are coincident.

If there is no distortion, the velocity of propagation in the line can be approximated by:

(14)

Reflection coefficient and transmission coefficient

There are two important concepts when a discontinuity is found in a transmission line. That discontinuity is usually present in connections between lines segments, medium changes in cable types, imperfection in the structure of the line, connections to loads, or anything else producing a mismatching. When a discontinuity is present, characterized by an impedance change regarding the characteristic impedance of the line, there will be part of the incident wave being reflected and part of the wave passing the mismatched point. The magnitude and phase of the effect of it in the incident waves is what the reflection and transmission coefficients are showing.

The reflection coefficient is function of the impedance with the line length, regarding its characteristic impedance:

(15)

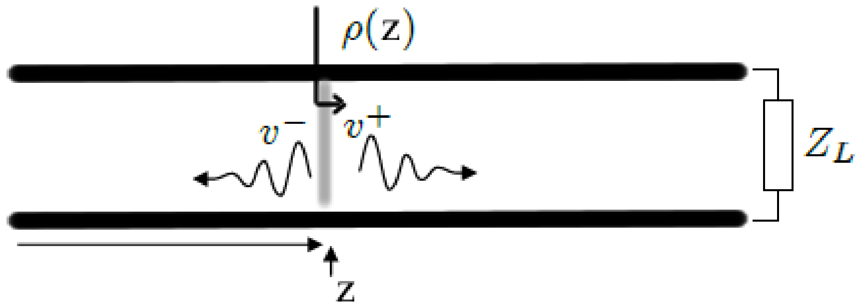


Fig. 4.4. Generalized reflection coefficient in a point z, with symbolic reflected and transmitted voltage waves.

Referred to voltage terms and from the input, the transmission coefficient will be:

(16)

It has to be considered that the path behind the discontinuity acts as a load, which will be conditioning these values in (15) and (16). The characteristic impedance can be the same as it was before the discontinuity is appearing, or it can be different. In any case, their magnitudes will be related with the difference between and . Another way to see the reflection coefficient is with its dependence of the propagation constant, in this case, referred to the input reflection coefficient ( ):

(17)

4.3.2 Line parameters through input impedance measurements

The impedance value along the z-axis, as was defined in Fig. 4.3 is determined by:

(18)

If both open circuit and short circuit are placed on the load side ( ), (18) can be simplified, in each case:

(19)

(20)

The combination of both equations yields the characteristic impedance value:

(21)

Then, the value of the propagation constant can be found by solving:

(22)

From (21) and (22), the line distributed capacitance and distributed inductance, taking into account their frequency dependence can be presented:

(23)

(24)

With these values, the velocity of propagation along the line can be calculated using (14), and approximating with median values of the distributed parameters:

(25)

4.3.3 Modelling the line

The circuital parameters based scheme seen in Fig. 4.3 can be repeated every *dz* distance to model the complete transmission line. This idea is followed in the scheme proposed in Fig. 4.5

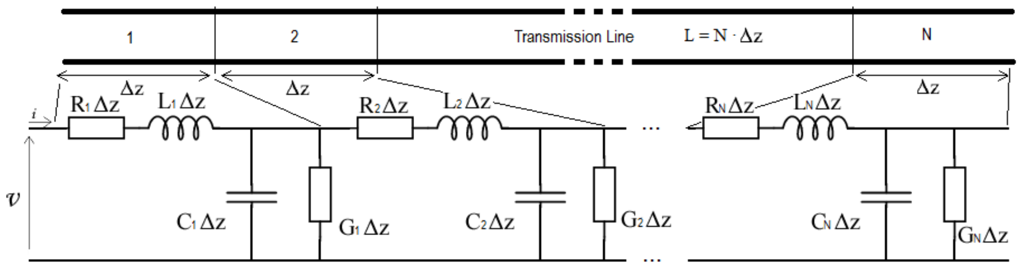


Fig. 4.5. Single-line diagram of distributed parameter circuit model.

If extra elements are put in the grid, they need to be modelled too in order to simulate the real behaviour of the whole system. As all the distributed parameters can be calculated through the input impedance measurements, there is a way to have a complete characterization of the grid for a certain type of cables and elements present in the network. For higher voltages there is an example [46] where this approach is used to characterize faults through calculations related to both current and voltage values in the transmitting-end. One of its main outcomes is how the proposed algorithm has a strong robustness to load variations maintaining a constant accuracy for LV distribution networks lengths.

With that idea in mind, one variation of that point of view regards obtaining a healthy-cable signature, and applying on it a fault location method. The results will be showing the response of that method to the healthy cable. Then, successive measurements in time can be compared with the original signature detecting any change in the power line. This is the same as measuring cables in their healthy state and apply them a fault location method once the LV grid is built. With the grid model it will be done using software with the simulated grid, supposing the structure of the grid already known. It has two main advantages. The first one is that there are no costs associated to the process of taking the signature of the cable more than knowing cable types and their length, and the joints or intermediate elements. The second advantage is to avoid taking useless signatures due to an already existent faulty state, mainly caused during the installation process.

4.4 Basics in fault location based in reflected pulses

4.4.1 Time-Domain Transmission

In this subsection a brief summary about how pulse echo is done, but instead of traditional TDR, which is based in one-end measurements, time-domain transmission (TDT) analysis will be used. It is based in the transmission time-response, implying one transmitter injecting one or more pulses in the line and a receiver, interpreting the received signal for a certain time period. It is related with the pulse echo techniques, because besides the transmitted signal reaching the receiver side in first term, there can be more related reflections, which will be in the receiver with a certain delay. This delay is related with the distance to every mismatch, which is producing reflections from the original signal, and contributing then to the received signal.

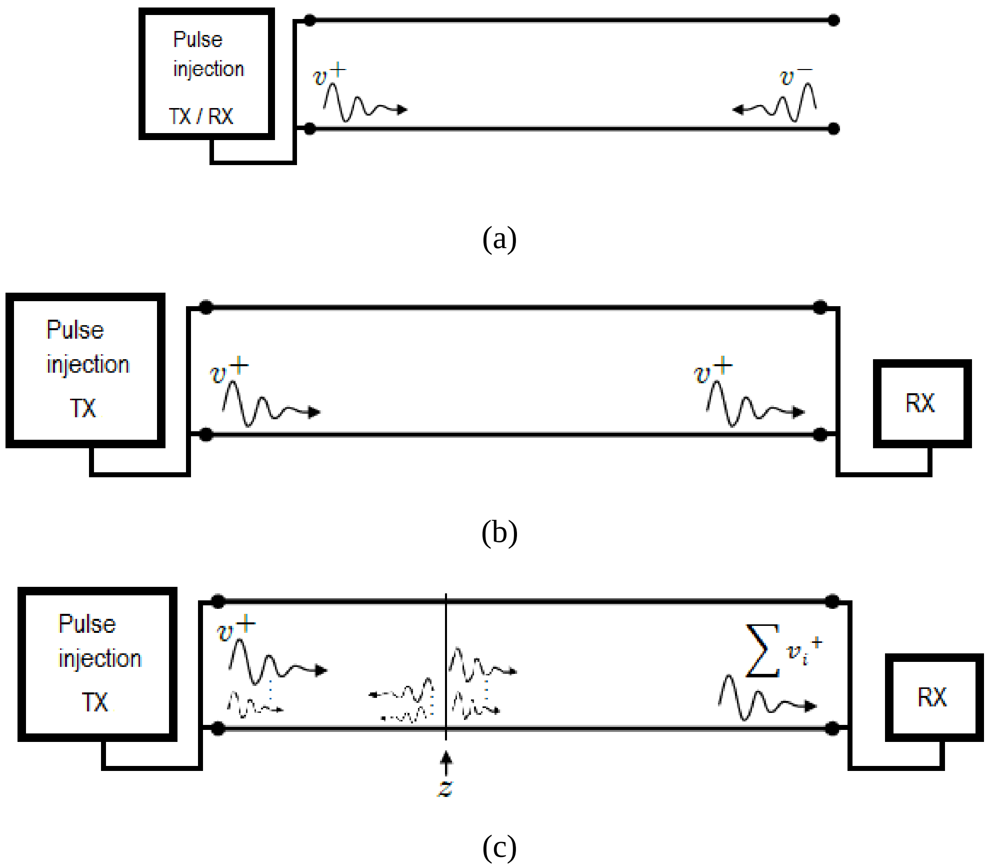


Fig. 4.6. Typical TDR configuration is shown in (a). TDT configuration with two ends involved is shown in (b) assuming a lossless matched line where the whole signal is arriving to the receiver. In (c) there is a mismatch in the point *z* of the line, causing many reflections which will be received in the far end.

In a lossy line, the period of time which all the reflected contributions can be considered will be given by how much attenuation is the line introducing. And that attenuation is related with the distance covered by each one of these contributions and all possible mismatches present in the transmission line which can be degrading the signal.

4.4.2 Getting TDT data from gain-phase measurements

If the gain and phase frequency response of a transmission line can be taken, then it is possible to rebuild that response in the time domain. If the transmitted signal is known, then the obtained signal can be analysed and the channel behaviour studied.

For fault location purposes, the main objective is to know about discontinuities in the lines and, above all, about undesired discontinuities which usually are representing faults. If a pulse is injected in a single and healthy continuous line, there will be only reflections from the far ends. But if there is any mismatch in the line, before the first reflection of the pulse will arrive to the receiver, there will be arriving reflections from the discontinuity. The distance covered by the main pulse in a line with a distance of *d* is:

$$— \quad (26)$$

The velocity of propagation in the line is related with c, through the velocity factor as it can be seen in (27). This factor is characteristic of each cable depending of its properties, but when a transmission line is measured there can be some factor changing the total value of the velocity of propagation for the pulse depending on connections and mismatches.

(27)

Based in the Fourier Transform properties, the Inverse Discrete Fourier Transform (IDFT) can be applied to the frequency gain-phase measurements and obtain the time-domain information. That is the discrete version used at software level of the Inverse Fourier Transform (IFT) shown in

(28)

The bandwidth of the frequency-domain signal is limited in practice. Because of this, windowing is used to limit calculations to a certain affordable limits. It implies a reduction of the time-domain response resolution, but usually the range of frequencies is enough to keep the necessary information inside the window to get a reliable time-domain signal.

From a frequency span, there will be a related time step ( ) for a N points frequency signal, following

(29)

And the time domain complete range can be reconstructed attending the number of points of the previous signal and the time step

(30)

The number of points utilized in the Fourier Transform should be at least four or five times the number of points of the frequency signal in order to get enough samples.

5 On-line condition monitoring

Actual fault location methods are mostly involving utility's displacement to the conflictive area. Since remote monitoring methods are being improved, it is being tried to reduce unnecessary costs of network supervision. But the main point is to have knowledge about the infrastructure current state to be able to make decisions. This type of pattern could be applied in multiple scenarios, and in LV distribution, where there are faulty cables already working, which are potential candidates to cause blackout or affect the PQ, it is not an exception.

Next, a system which could face this problem of fault location on power lines is presented. Some previous experiences in on-line monitoring of faults are showing how intermittent and incipient faults can be detected. For example [47] is presenting and testing new monitoring techniques in real networks. It is based on transients monitoring and recording when there are those unusual behaviours of a monitored signal between two monitoring devices using synchronized Travelling Wave Fault Locators. Once it is detected a possible faulty state, TDR is employed to know about the location of the fault.

One problem of this system could be that it is not facing completely the problematic of the complexity of the grid to analyse the signal because it is acting only in single segments and in order to take into account branches it is necessary to incorporate as much devices as branches are. Another limitation is how those devices are not permanently placed into the network. They are left where the cable to be checked is for several hours or days, needing operator displacements even when cables can be healthy.

A constant monitoring system capable to detect LV faults and to be integrated in the network is needed. In the next subsections a description of how this system could be implemented and which is necessary to make on-line fault location feasible is explained.

5.1 Detection and location of the fault by signal processing

5.1.1 Software-Defined Radio based device: brief description

Composed by a baseband processor as the field programmable gate array (FPGA), analog to digital and digital to analog converters (ADC/DAC), digital up and down converters, and both transmitter and receiver modules, this devices can perform almost any operation that could be done with traditional hardware components. But the processing capabilities are now implemented by software, reducing costs and increasing the signal processing flexibility [48].

In [49], experimental result obtained using software-defined radio (SDR) are presented for slope monitoring.

5.1.2 Fault location purposes

Those software capabilities can be used to implement different fault location techniques. Technique presented in [34] is using a sine wave generator operating from 30 to 100 MHz which is converted to a square wave through a PN sequences generator. Then a binary phase shift-keyed signal is generated and it is injected into the line under test. In that paper, signal is reflected in the network and it feds a correlator circuit where injected and obtained signal are compared. The points of interest of this technique are the use of a wide spectrum, which can cover high frequencies and the use of correlation analysis to process the response from the network.

If this technique is carried out to a two ends communication, the injected signal could be recorded in a receiver at customer's end and sent back to the transmitter, which could be placed in the substation side. If this transmitter has processing capabilities presented for SDR technology, it can take every response from receivers and compare it with the original signal. The result will be then compared using the same processing guidelines for a simulated healthy branch. And it will be done in that substation side using software capabilities of the transmitter.

That simulation of the healthy branch consists in seeing how the original system will respond in every end of the grid. If the grid can be modelled, that is, if a fingerprint can be obtained using a distributed parameters model, then the response to that model can be obtained for every customer's end. These responses from the healthy cable can then be compared with those that are being obtained in each measurement seeing if there is any change.

5.1.3 Grid fingerprint

Based on SDR nature where signal processing can be done without expensive hardware components, it is proposed how to simulate the communications channel of the distribution network and compare its healthy state with possible faulty states. The main idea to get the fingerprint of the grid, involves previous knowing of:

- Elements that are present in the grid
- Line distances
- Electrical characterization of every component

If it is considered that the LV distribution grid is reduced to cables and joints, they could be characterized knowing their individual characteristic and simulate a model of the concrete grid as a whole. It is important to have an accurate fingerprint to be compared with consecutive measurements of power line condition. As accurate it will be, lower impedance changes will be detected. For this reason it is necessary to build a precise model, for example using line modelling as it was presented in 4.3.3. This will be the fingerprint of the line to be used as the base of the simulation. Once this model is built, the fingerprint of the response using the previous spread spectrum technique can be obtained referred to that communications channel represented by the grid.

5.2 On-line fault location implementation

5.2.1 Possible implementation

The increasing expansion of automatic meter reading (AMR) devices in the network and the efforts put in it as an active participant on the Smart Grid can be exploited including in their structure an extra functionality regarding fault location. A plug-in could be incorporated to the actual AMR’s hardware, composed by one receiver, one memory and the interface communicating both structures. These receivers in each customer end can be taking advantage of the communications capabilities of the actual AMR meters and communicate with the transmitter placed in those substations, which want to be monitored. As it was pointed out in the previous section, the transmitter unit can process the information given by each customer end and decide if there is a fault in the system.

One problem to face is the adaptive character that the system should have in order to get accurate responses. For that, if the instantaneous load behaviour of the network measured from every end could be done, it will be sent to the substation side and it can take part in the grid simulation. For example, and in terms of reliability, loads state can be monitored during nights, where the frequency response has not the same variations as it has during the day [50]. That means that it is more suitable for signal analysis.

In a real scenario, it has also to be considered how to filter out signals and reflections from the field bus, in order to isolate the complete sub-branch of the distribution system from the other sub-branches on the substation side. For doing that, inductive filters presented in [26] can be placed for each branch header.

A description of how actual AMR network is working and how this on-line monitoring method can be integrated is presented in [51]. It also shows an economical study about the reliability of this system.

5.2.2 Advantages from fault location point of view

Moreover of the AMR system integration possibility, there are some interesting aspects about implementing this, for example that only receivers are needed at customer's ends, which avoids the costs of including complete fault location devices there. And also, as it was mentioned before, the on-line monitoring advantages.

Attenuation and disturbances, two of the most important problems in PLC are faced from different points of view for fault location purposes. First, employing TDT instead of TDR, which is reducing the return path associated attenuation. Also it has to be considered how original SSTDR is facing noise and is it able to detect lower impedance changes, regarding traditional methods.

The next step, and in order to know how those power line communication channel changes are, there will be an exhaustive study in next chapter about how faults affect that channel and if faults can be detected with the proposed methods before they enter in a permanent faulty state.

6 Laboratory analysis

6.1 Introduction

Once it is known how to characterize cable and how a model of the network can be done, the study of real cables in the laboratory is required to validate the model. In this case, the validation is done attending high frequencies, seeking for a balance with the attenuation penalization considering the effects of increasing frequency.

Three different scenarios were proposed. However it has to be bear in mind that the final aim is to detect how channel behaviour changes with a fault appearing in the network. First, an analysis of how two different types of faults are evolving is done. These are phase to ground and phase to phase, usual faults involving one phase or two or more, respectively. All the faulty situations are made putting the fault under water, in order to simulate the maximum moisture conditions which the cable can be exposed. That is the point for the long term measurements performed in the second step, to see how cables are responding to a continuous moisture exposure during hundreds of hours, and how cable’s insulation performance is evolving in a longer period. In a third step, a branched scheme has been studied. To do this it is necessary to know how a single cable works. Then, with every single segment is already characterized, complexity is added by building a small grid. This last step allow to recognise if what is seen in single segments is prevailing regarding the complexity added, and which is the contribution for the results.

Cables presented in 2.3 are used to perform the analysis in the two first steps. In the third step only AXMK cable, which is presenting better attenuation performance, is chosen.

The following is a detailed explanation of each of these points, explaining the test setup used and which measurements were made.

6.2 Faulty cables characterization: test bench

A set of measurements were performed to a single cable segment of 50 meters. They were based in the impedance analysis of high frequencies, because of its possibilities for calculating cable parameters that were presented in previous chapters.

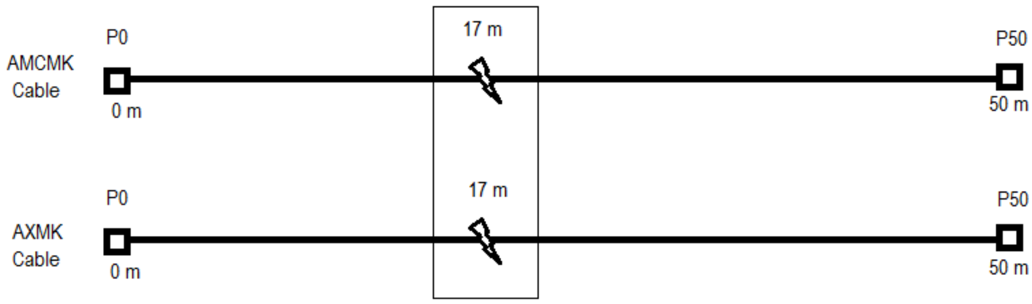


Fig. 6.1. Both studied underground LV cable ports configuration with the fault placed before the middle point (17m from P0).

Furthermore, input-impedance measurements, an insulation resistance test and a leaking currents checking process were performed. Both additional tests are pretending to show when cable's damage is enough to fail the insulation test, which generally means that leaking currents will be starting its appearance. Once the cable is measured in a healthy state, different insulation degradations are performed and the cable is measured again. The rising fault is placed 17 meters from the port 0 (P0) as it is shown in Fig. 6.1.

To simulate that rising fault, different degrees of damage were performed at the faulty point. Every fault stage is characterized by one or more different time-spaced measurements, depending on the previous expectations to get any change in the results.

6.2.1 Measurements setup

The main purpose of the following measurements is the characterization of the cables. As it was seen in the 4.3.2 chapter, this can be done through input-impedance measurements. Besides, a series of additional measurements are performed to take knowledge about how impedance changes are conditioning other cable parameters, if they are. These measurements are an insulation resistance test, S-Parameters analysis, and the study of leaking currents appearance.

6.2.2 Coupling

All tests are performed off-line but the leaking currents test, which is performed under 220 V applied voltage during short periods of time. These all tests are pretending to get a signature of the cable behaviour and it cannot be done with a loaded scheme. Moreover, available analysers need to operate in uncharged cables with direct coupling. There is the possibility of including coupling interfaces, but in a first term the additional complexity added by those interfaces were wanted to be avoided.

In [52], it can be seen how inductive coupling interfaces are used to perform communications between two universal serial radio peripherals (USRPs) in the PLC channel. These types of interfaces are being used to perform tests in energized lines without customers' disconnection.

6.2.3 Input-impedance measurements

To perform these measurements a Hewlett-Packard 4194A Impedance Analyser with an impedance probe kit HP 41941A is used. Frequency range is limited to 100 MHz, and all measurements will be at the range of 100 kHz - 100 MHz. Previous studies PLC channel modelling used to be related to lower frequencies. An important study, is which [45] performed, analysing the channel up to 30 MHz. The main reason to adopt this point of view is the attenuation penalization.

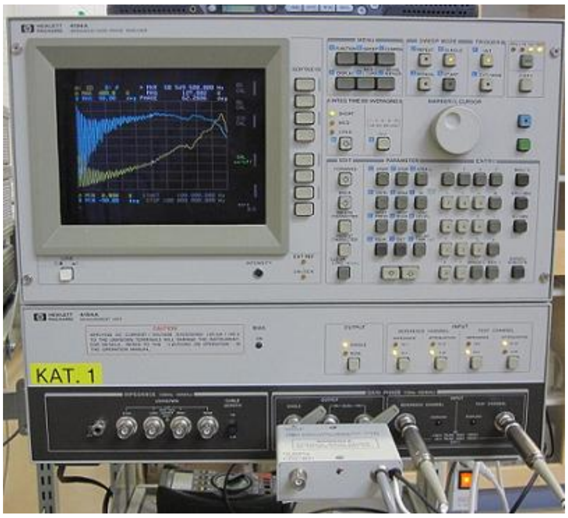


Fig. 6.2. HP 4194A impedance analyser used in magnitude-phase impedance measurements.

For fault location purposes, it was seen that novel methods, such as those seen in chapter 3.5 are facing this problem and allow taking new channel perspectives. Aside of this aspect, available previous studies of the PLC channel are covering different frequency ranges surveying its impedance behaviour. In [53] an indoor analysis is covering frequencies up to 70 MHz, and with a wider range, [54] presents a technique of impedance measurements up to 500 MHz.

Cable conductors measured, that is phases were (L1, PE) in the phase-protective earth case, and (L1, L2) for the AMCMK cable and (L1, L3) for the AXMK cable in the phase-to-phase case. These two combinations are giving enough information for cables characterization regarding the rest of possibilities. They are also corresponding with the nearby and the opposite conductor in the four conductor cable case.

6.2.4 Leaking currents analysis

This test is performed in every fault stage. To see if there is any current leaking from the faulty phases, a copper plate is placed 33 mm below both cables, covering the 15 mm long part of the cable where a half of the sheath will be removed. This copper plate is connected through a wire making a return path for currents representing a possible phase to ground fault, as seen in Fig. 6.3.

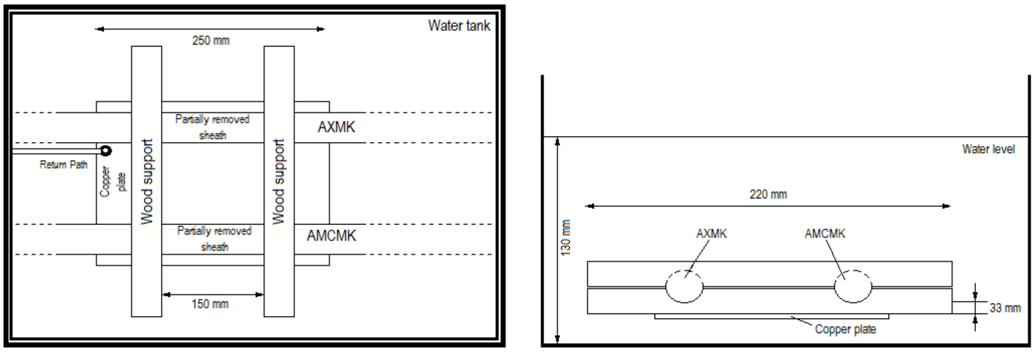


Fig. 6.3. Water tank setup to perform parallel measurements with both cables. A copper plate is attached them from a fixed distance.

It is necessary to point out that the water used in the experiment is tap water. Due to the previous treatment that it is subjected, impurities cannot be close to the real moisture scenario. Moisture present in soil, for example, can be adding a certain degree of impurities. It is implying a faster insulation degradation and, because of this, a faster appearance of leaking currents. In [55] and [56], a complete study about moisture influence in aged cables is done, with a detailed study of insulation-related loss tangent (δ) variations. Water penetration and its axial diffusion can be seen, and also is explained how water ingress can be detected directly using TDR, what means that there is an immediate change on impedance characteristics. This study is performed in 10 kV cables, but those results can be a clue for lower voltages.

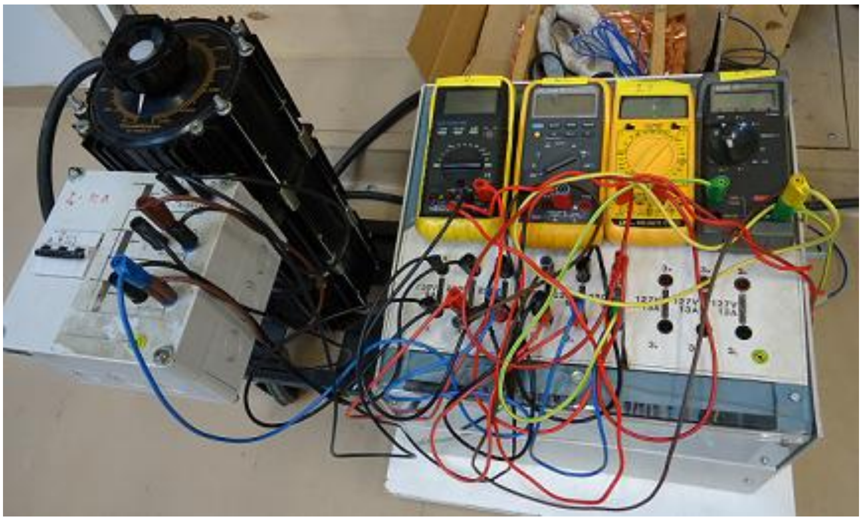


Fig. 6.4. Variable output primary transformer and intermediate transformer for galvanic isolation purposes. The current of phases involved in the fault is monitored using multimeters, and also the current return path to control leakages is measured.

In [57] some tests with oil-impregnated-paper insulation LV cables were performed, seen how the water distribution was not uniform along the affected cable stretch. Furthermore, water diffusion is also related with the bend radius described by cable position or with the temperature. There is also explained how the time to penetrate the insulation is depending on moisture conductivity.

In this test bench, water is in accordance with room temperature, rounding around 23 ºC. Supply voltage of 220 V is used to energize the cables. Transformer setup with the multimeters utilized to see every phase and the return path is shown in Fig. 6.4.

6.2.5 Insulation resistance test

Deterioration in cables' insulation can be seen performing this test. In this case, the line is energized injecting 380 V between phases in each measurement. Insulation resistance tester receives an immediate response from the injected signal and shows the value returned by the cable. A healthy cable response is answered with > 1000 MΩ results, which is indicating a proper isolation.

For both cables multiple combinations were measured, including (L1, L2), (L1, L3), (L2, L3), (L2, PE), (L3, PE), (L1, PE) and (L1+L2+L3, PE) depending on the phases affected by the destructive tests.

6.3 Phase to ground fault

6.3.1 Setup

One of the phases is damaged in 4 stages, leaving the cable several hours under water to allow water ingress. Measurements recorded are presented in Table 6.1.

Table 6.1. Stages describing the phase-to-ground fault.

Stage	**Damage description**		**Hours**
	AXMK	**AMCMK**	
Healthy	-		-
Healthy in water	Healthy cables placed in the water tank. There is no water penetration under the sheath		-
Cut dry	50 mm cut in the sheath, dry environment		-
Cut in water	50 mm cut in the sheath, water submerged		00:30 h
			01:30 h
			03:00 h
Sheath cut	150 mm long of half of the sheath removed		04:00 h
1st degree fault	5mm visible core in L1	33x3 mm fault in L1	01:00 h
			02:00 h
			25:00 h
2nd degree fault	15mm x 3mm visible core in L1	33x5 mm fault in L1, deeper insulation damage	00:30 h
			02:30 h
			69:00 h
3rd degree fault	30mm x 3mm visible core in L1	15mm x 3mm of conductor exposure inside the 33 x 5 mm damaged area (L1)	00:30 h
			02:30 h
			21:30 h

All the stages considered were though as possible previous states to a permanent fault, when phases can become in an open/short circuit and being totally damaged. A visual description of each cable damage stage is presented in Appendix I.

6.3.2 *Input impedance*

AXMK

A frequency sweep from 100 kHz to 100 MHz is made. Upper frequencies, from 80 MHz are introducing some errors due to the analyser's maximum frequency of operation, at 100 MHz. Lower limits are defined for those frequencies where impedance variations start. In Fig. 6.5 a comparison between four cases shows how differences are starting in the 10 – 20 MHz range and from 80 MHz they start to be unpredictable.

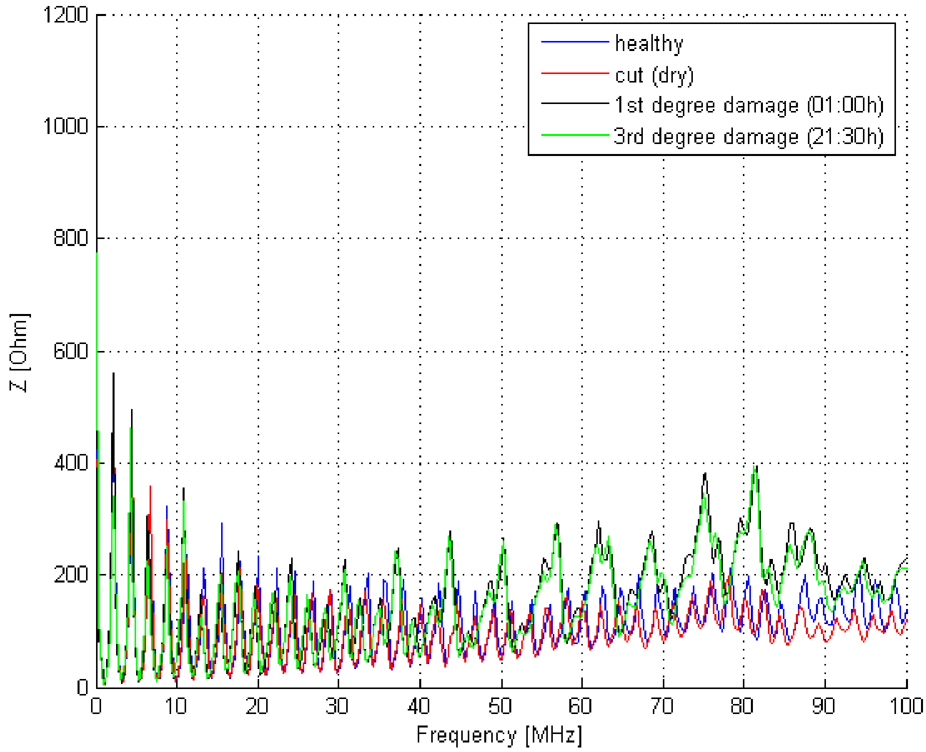


Fig. 6.5. AXMK cable, input impedance between L1 and PE in the observed frequency range.

As it can be seen in Fig. 6.6 with a detailed zoom in the 30–50 MHz range, all curves from different fault degrees under water are describing different impedance behaviour with the frequency regarding the stages where the cable was already dry. Specifically, there are some interesting frequencies where slopes in curves with the cable dry are coinciding with impedance peaks in curves where there is water under the sheath. There are cases, for example in 37 MHz or in

43.5 MHz where measured difference is around 200 Ω. In novel fault location methodologies as the presented by [35], changes of that magnitude can be notoriously detected.

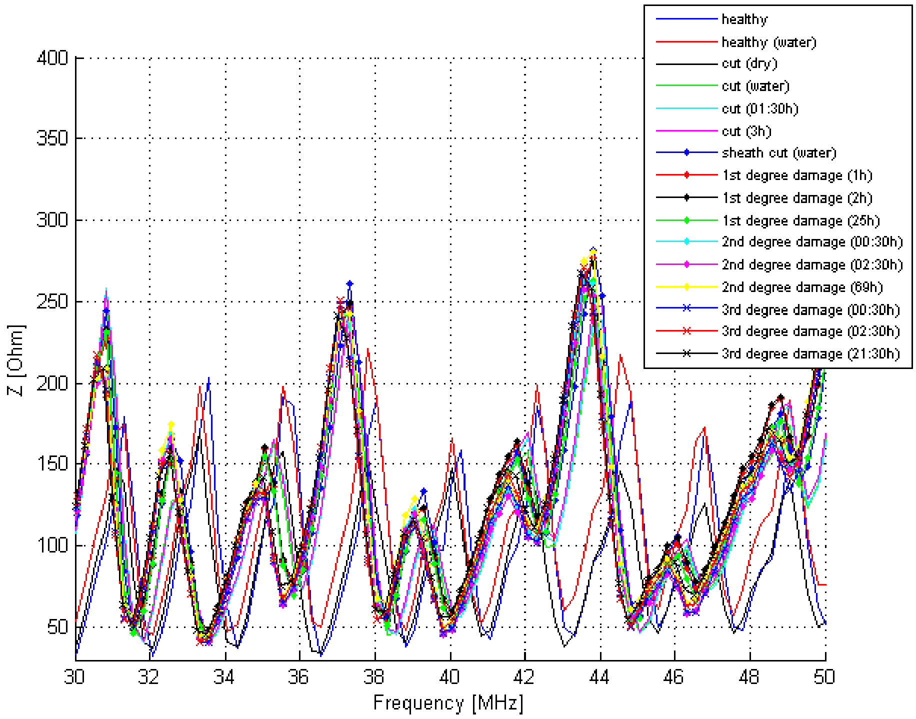
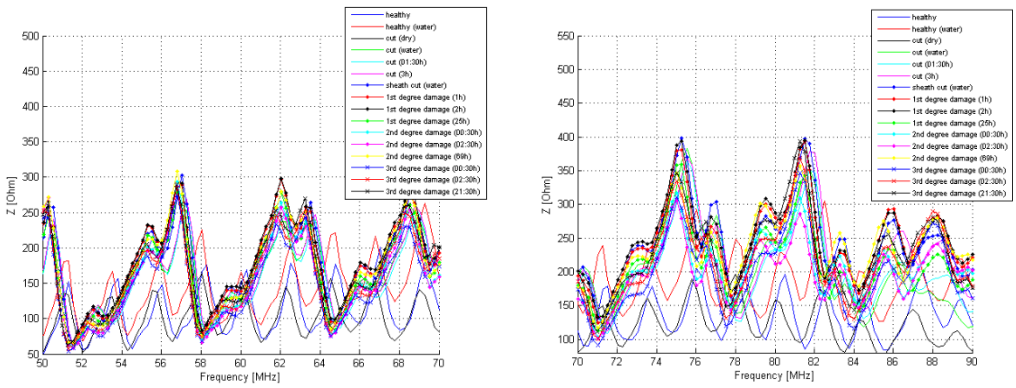


Fig. 6.6. Phase-to-ground fault: AXMK cable (L1-PE), from 30 MHz to 50 MHz.



(a) (b)

Fig. 6.7. Phase-to-ground fault: (a) AXMK cable (L1-PE), from 50 MHz to 70 MHz and (b) from 70 MHz to 90 MHz.

It is necessary to keep in mind that those changes are taken in a single cable and with a reasonable distance. Increasing distance or introducing branches may probably make those differences lower due to attenuation and reflections effects. Despite of that, it is showed that there are two clear situations observed on impedance measurements: curves where the fault is dry and curves where the fault is surrounded by water. Similar results are obtained between phases L1-L3, which are opposite compared to the conductor structure in AXMK cable phases as it is showed in Fig. 6.8 and Fig. 6.9, up to 70 MHz.

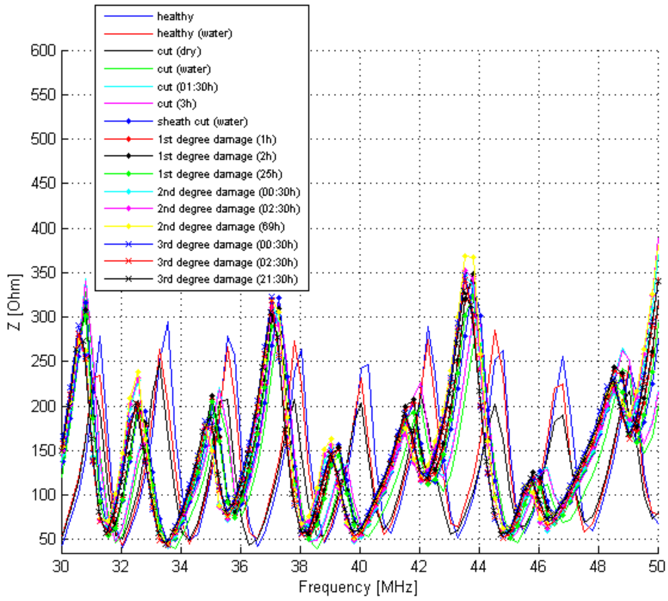


Fig. 6.8. Phase-to-ground fault: AXMK cable (L1-L3), from 30 MHz to 50 MHz.

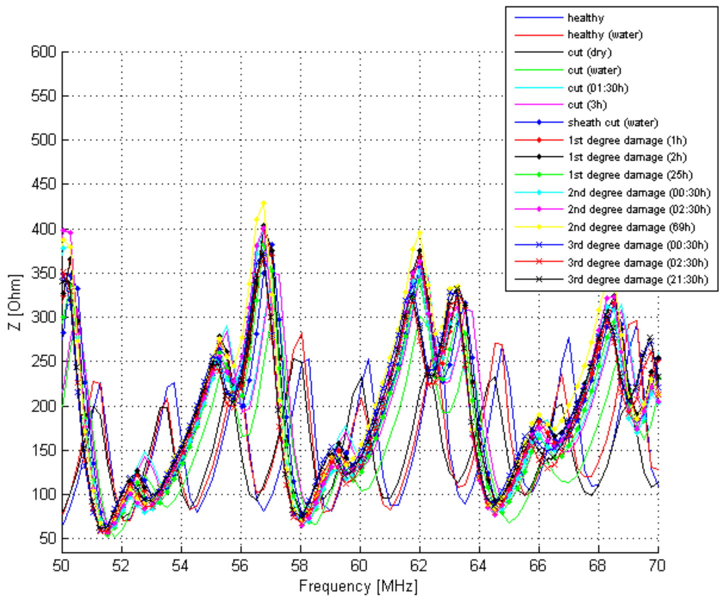


Fig. 6.9. Phase-to-ground fault: AXMK cable (L1-L3), from 50 MHz to 70 MHz.

AMCMK cable

In the PVC insulated AMCMK cable corresponding measurements were performed. It is shown in Fig. 6.10 how input impedance is more accurate in low frequency ranges and there is higher attenuation penalizing signal quality. It is causing the effect of seeing fewer reflections, not because of they do not exist but because their amplitude is being reduced both frequency and distance effects.

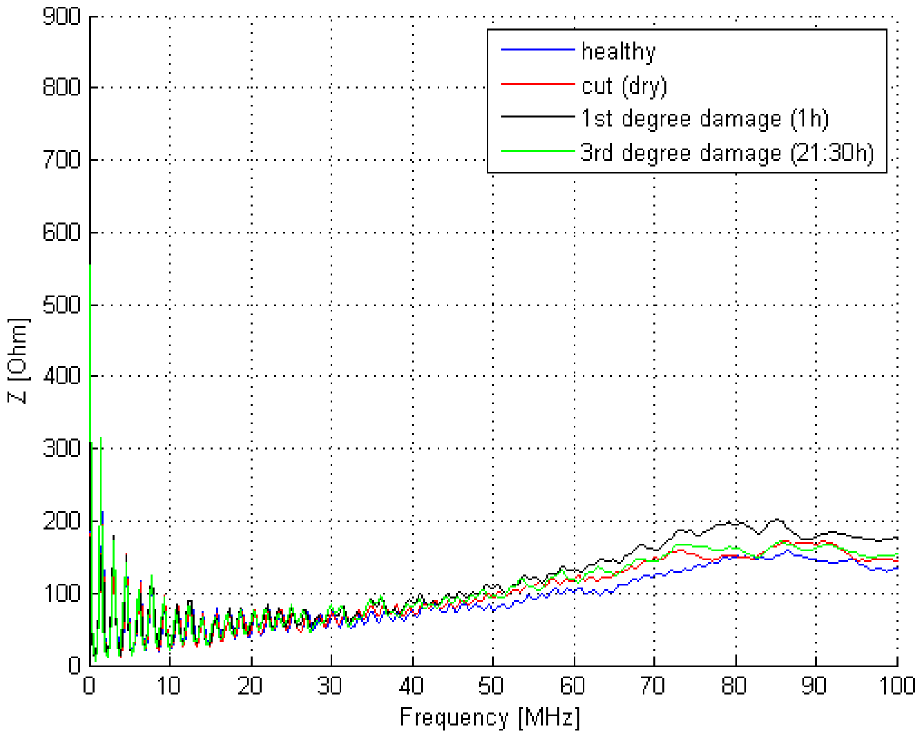


Fig. 6.10. AMCMK cable, input impedance measurement between L1 and L2 in the observed range.

The effects commented for the AXMK cable in lower and upper frequencies are remarked now. All the four representative curves showed have a similar response almost up to 20 MHz and are showing clear behaviour differences from 70 MHz. It is also seen, how the impedance response is decaying once it is reaching those frequencies, while the expected frequency response should continue growing with the frequency.

Measurements taken between phases L1-PE are also penalized in high frequencies, showing random behaviours. That is due the difference between connections made with L1 and PE and with L1 and L2. The concentric PE conductor has different physical and electrical characteristics from the aluminium cores used in every phase, and also from the PE of the AXMK, which is giving a similar response than measured phases.

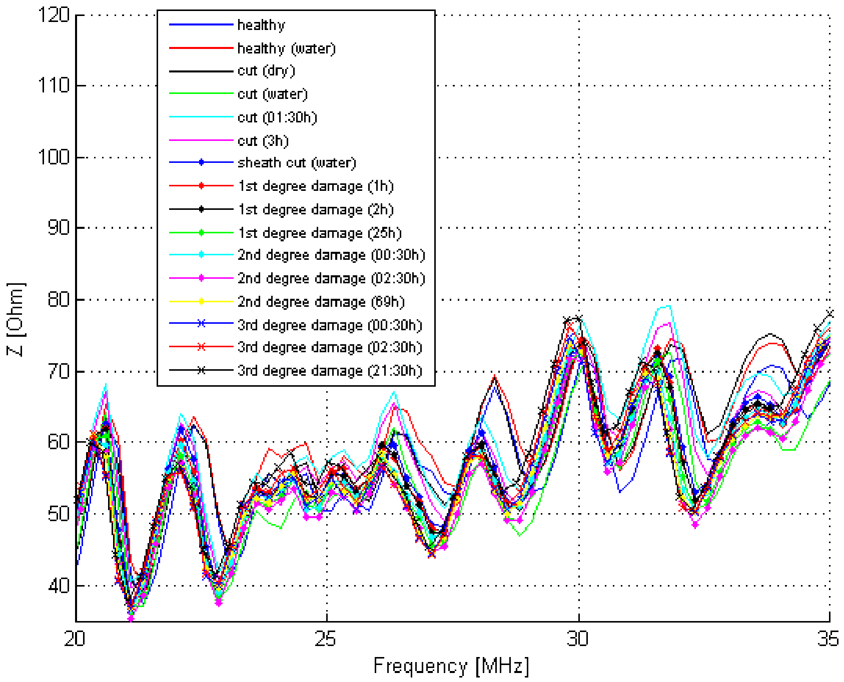


Fig. 6.11. Phase-to-phase fault: AMCMK cable (L1-PE), from 20 MHz to 35 MHz.

From Fig. 6.11 and Fig. 6.12, it can be seen how differences are much smaller than in the AXMK case, and opposite slope-peak situations regarding dry and wet surrounded fault are fewer. Measured impedances between L1-L2 detailed view is shown in Fig. 6.13, where curves are more consistent than those seen in Fig. 6.11, but differences between dry and wet states remain the same.

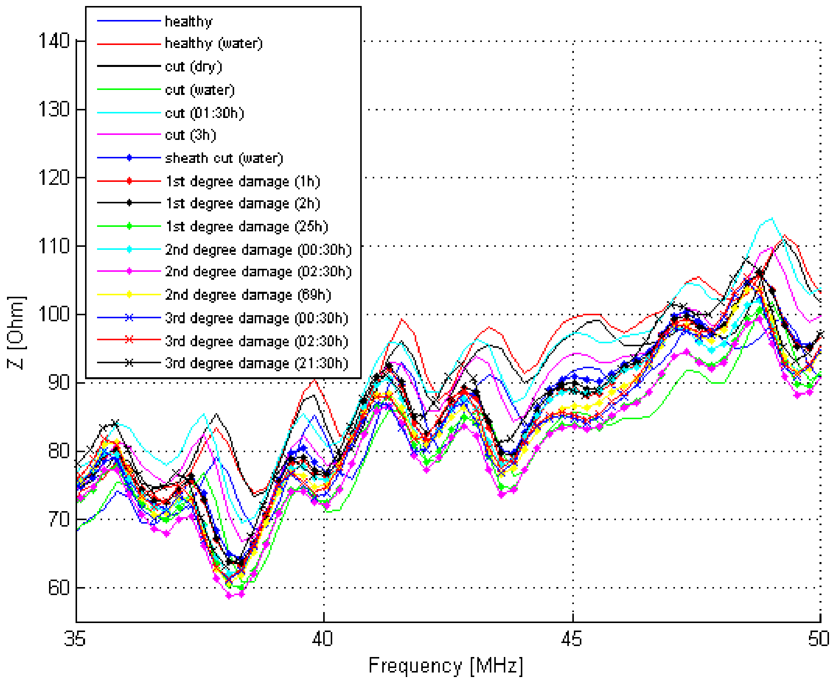


Fig. 6.12. Phase-to-phase fault: AMCMK cable (L1-PE), from 35 MHz to 50 MHz.

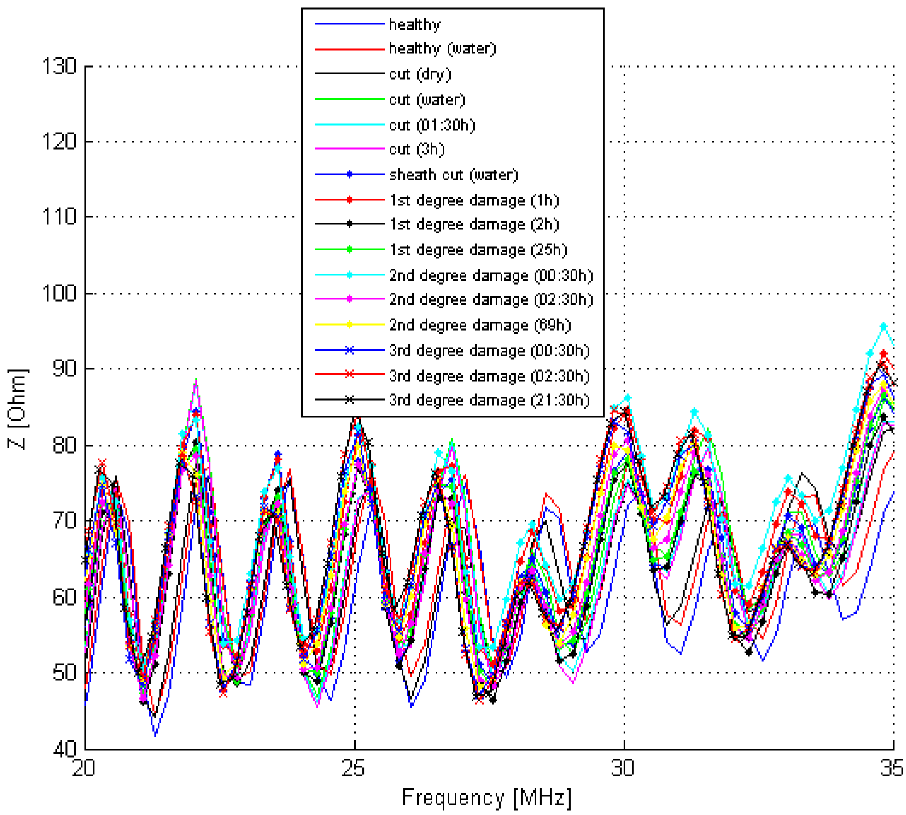


Fig. 6.13. Phase-to-phase fault: AMCMK cable (L1-L2), from 20 MHz to 35 MHz.

6.3.3 Attenuation

Through input impedance measurements, attenuation (coefficients) curves can be obtained as it was seen in chapter 4.3.1. All these attenuation curves as a function of frequency were put in logarithmic form and referred to each 100 meters long step. This is in order to relate curves with distances usually used in LV distribution grid. Then they were fitted to make curves interpretation easier using a 9th degree polynomial fit. Results for both cables are shown in Fig. 6.14 and Fig. 6.15. It can be seen how those fewer differences in AMCMK cable cause also fewer differences on estimated curves. However, there is a clear evolution on degradation between both dry and wet cases in the AXMK cable calculated attenuation.

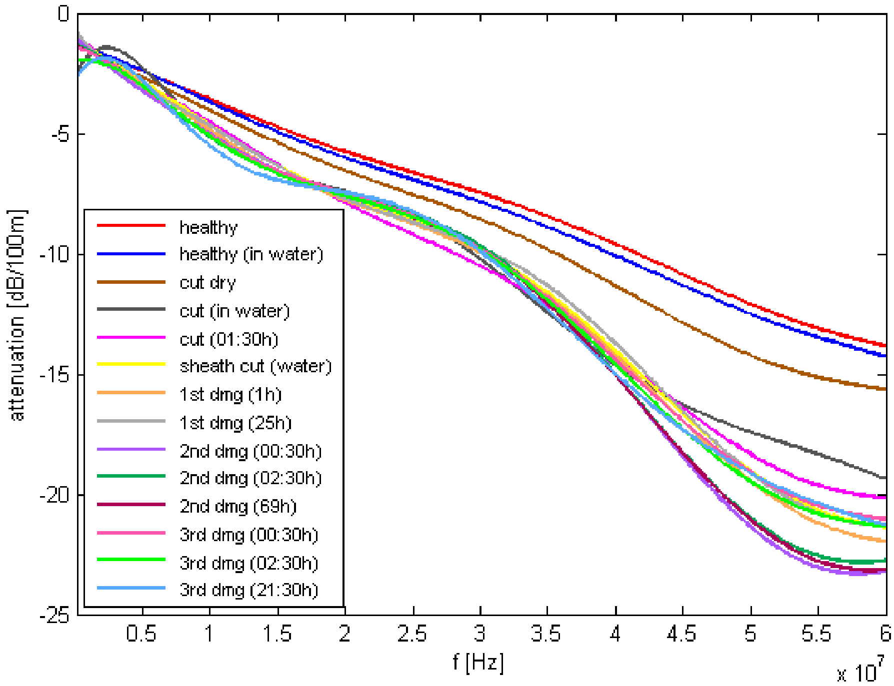


Fig. 6.14. Phase to ground case signal cable attenuations up to 60 MHz (AXMK cable, L1-L3).

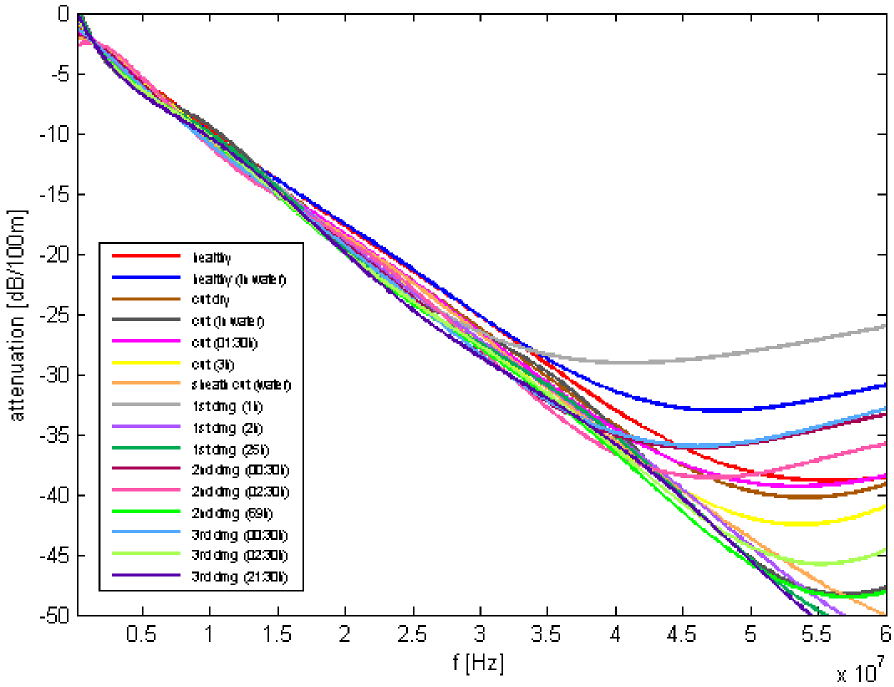


Fig. 6.15. Phase to ground case signal cable attenuations up to 60 MHz (AMCMK cable, L1-L3).

6.4 Phase to phase fault

6.4.1 Setup

In this type of fault, at least two phases are involved. Table 6.2 shows the different damages done between (L1, L3) for the AXMK cable and between (L1, L2) for the AMCMK cable.

Table 6.2. Stages describing the phase-to-phase fault.

<table>
<tr><th rowspan="2">Stage</th><th colspan="2">Damage description</th><th rowspan="2">Hours</th></tr>
<tr><th>AXMK</th><th>AMCMK</th></tr>
<tr><td>Healthy</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Sheath cut dry</td><td colspan="2">150 mm long half of the sheath removed, dry environment</td><td>-</td></tr>
<tr><td>Sheath cut wet</td><td colspan="2">150 mm long half of the sheath removed, wet environment</td><td>-</td></tr>
<tr><td rowspan="4">1st degree damage</td><td rowspan="4">L1:30x5 mm insulation damage (with 5x5 mm area of exposed conductor)
L3:20x5 mm i.d. with 12x3 mm of e.c.</td><td rowspan="4">30 x 5 mm in L1 and L2</td><td>00:30h</td></tr>
<tr><td>05:30h</td></tr>
<tr><td>24:00h</td></tr>
<tr><td>30:00h</td></tr>
<tr><td rowspan="2">2nd degree damage</td><td rowspan="2">L1 and L3: 15 mm long removed insulation</td><td rowspan="2">L1 and L2: 15 mm long cut with exposed conductors</td><td>17:00h</td></tr>
<tr><td>18:00h</td></tr>
</table>

This fault type can be more critical than the phase to ground type because now there are two different phases with supplied voltage, and the possibility of a short circuit making the fault permanent grows.

6.4.2 Input Impedance

AXMK cable

With the previous experience of the ground to phase fault simulation, this new fault type can be synthetized in few measurements. Taking more samples in time of the fault effect on cable degradation is not assuring clear changes, as it is proved before and as it is seen in practical scenarios where faults are present during months or even years. Those changes were only seen when water penetrates under the sheath. But now it is checked if phase to phase faults can accelerate and make more noticeable changes on channel signature.

A detailed view of the 10 MHz to 70 MHz range is shown below, with frequency steps of 20 MHz for the L1-PE phase relation.

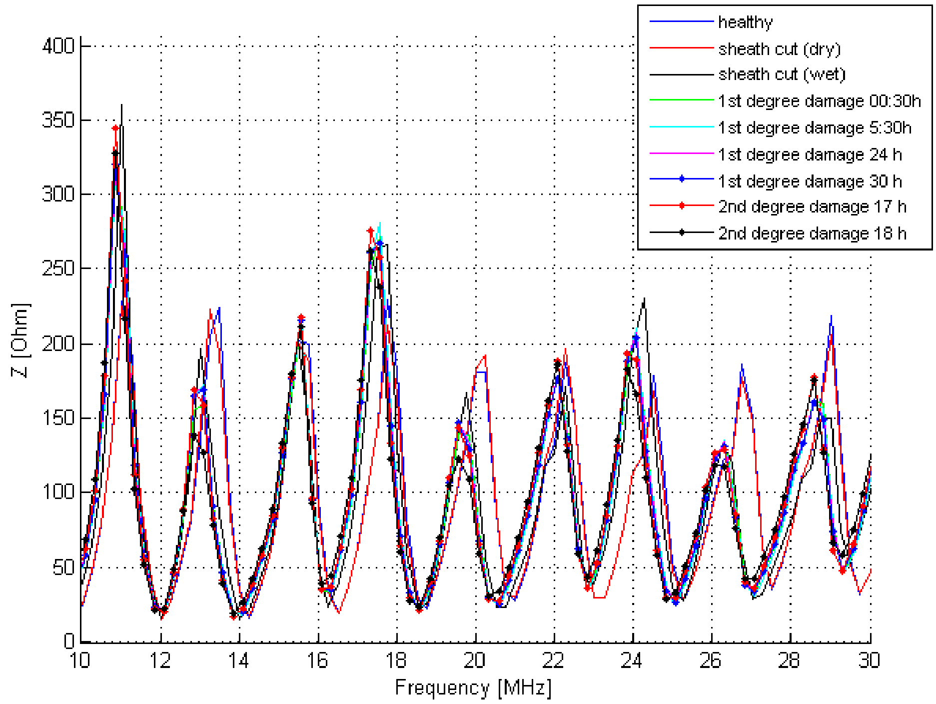


Fig. 6.16. Phase-to-phase fault: AXMK cable (L1-PE), from 10 MHz to 30 MHz.

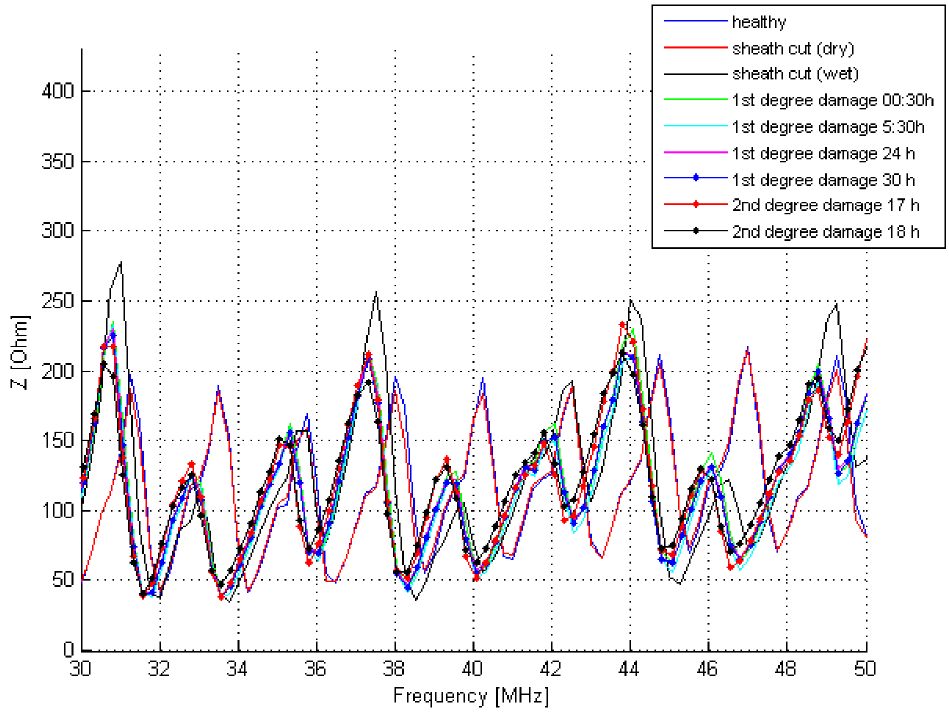


Fig. 6.17. Phase-to-phase fault: AXMK cable (L1-PE), from 30 MHz to 50 MHz.

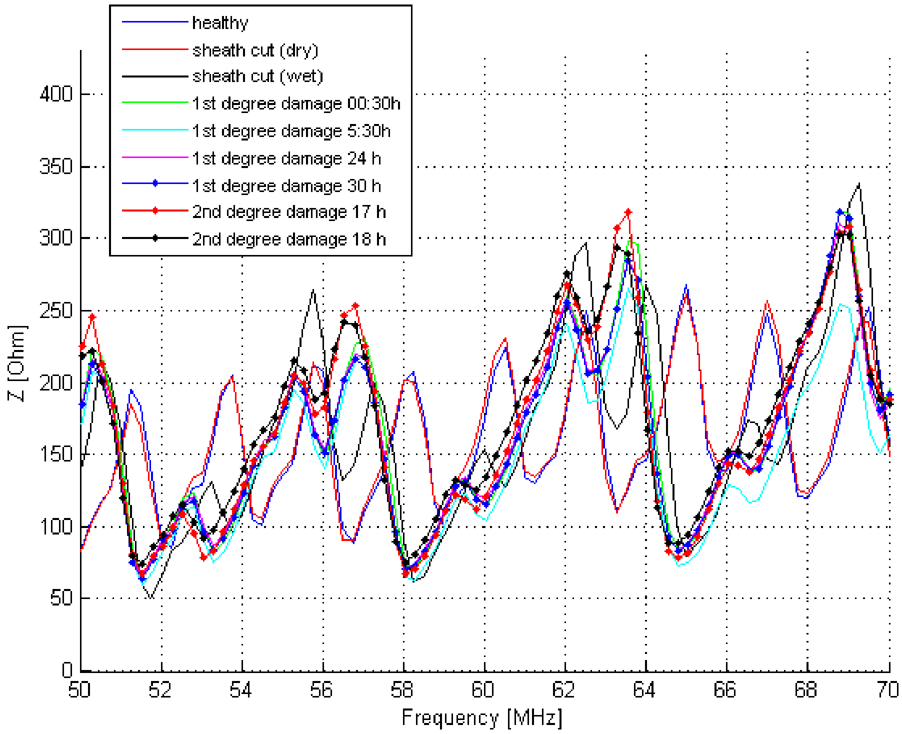


Fig. 6.18. AXMK cable (L1-PE), from 50 MHz to 70 MHz.

First differences start to be visible on peaks delay around 20 MHz and 27 MHz, but the main changes are visible in Fig. 6.17 and Fig. 6.18. Again there are coincidences between peaks and slopes because of the differences in their capacitive behaviour affecting impedance measurements. On wet stages, peaks are becoming high but their number is decreasing regarding dry measurements, with more peaks close in frequency but with lower amplitude. Comparing with phase to ground impedance signature, those differences are lower but still remains noticeable.

Attending to L1 and L3 input impedance, differences are quite high. As it can be seen in Fig. 6.19, there are peak-slope coincidences for both cases keeping impedance variations close to 300 Ω. When frequency is reaching frequencies up to 70 MHz (Fig. 6.20), curves start to present more variations as it was observed in previous chapter.

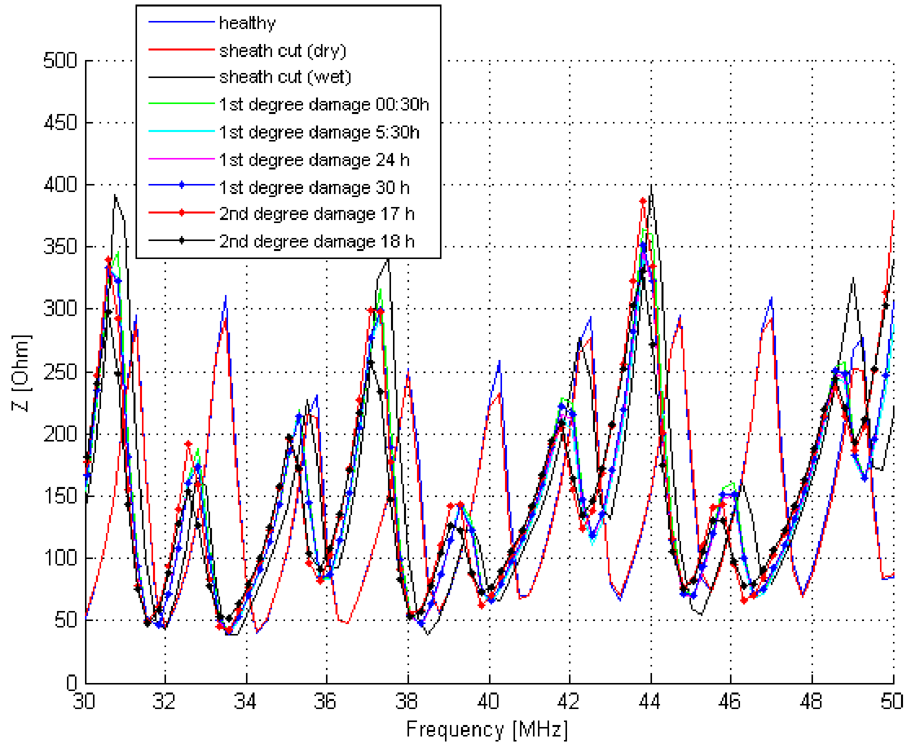


Fig. 6.19. Phase-to-phase fault: AXMK cable (L1-L3), from 30 MHz to 50 MHz.

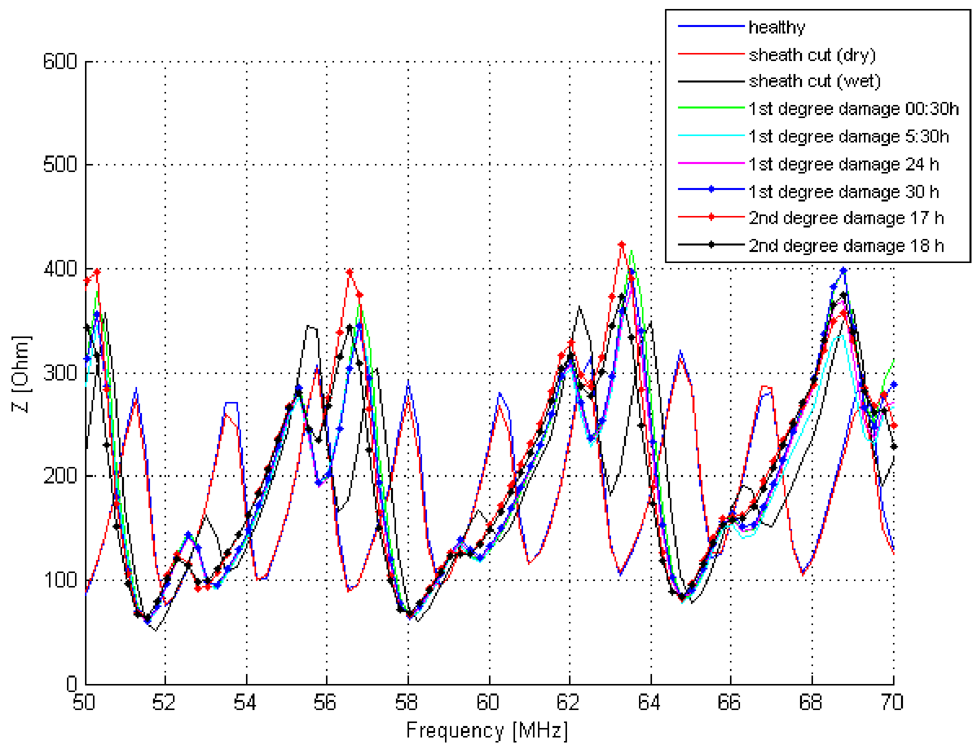


Fig. 6.20. Phase-to-phase fault: AXMK cable (L1-L3), from 50 MHz to 70 MHz.

AMCMK cable

There are no remarkable changes in the AMCMK cable until the second degree damage is done.

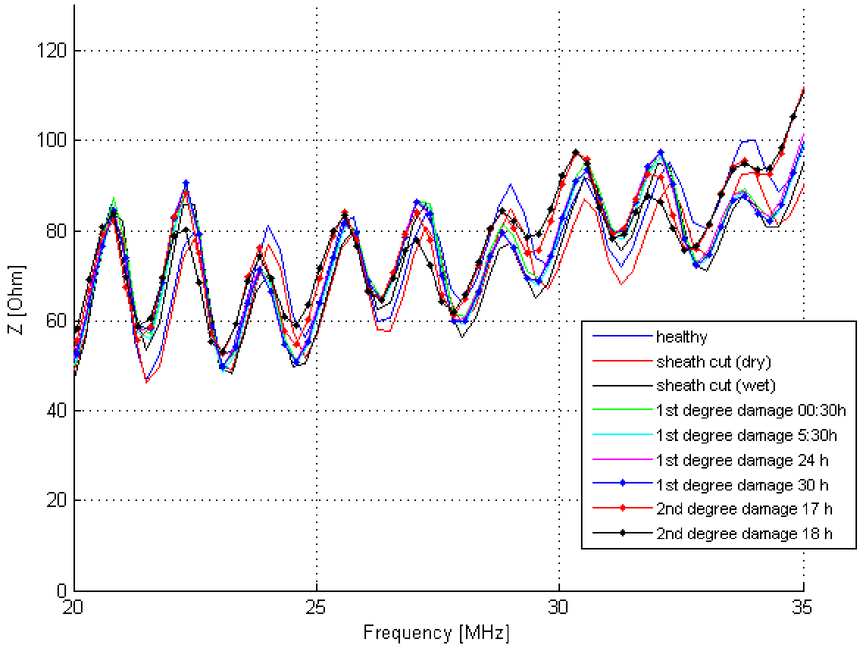


Fig. 6.21. Phase-to-phase fault: AMCMK cable (L1-L2), from 20 MHz to 35 MHz.

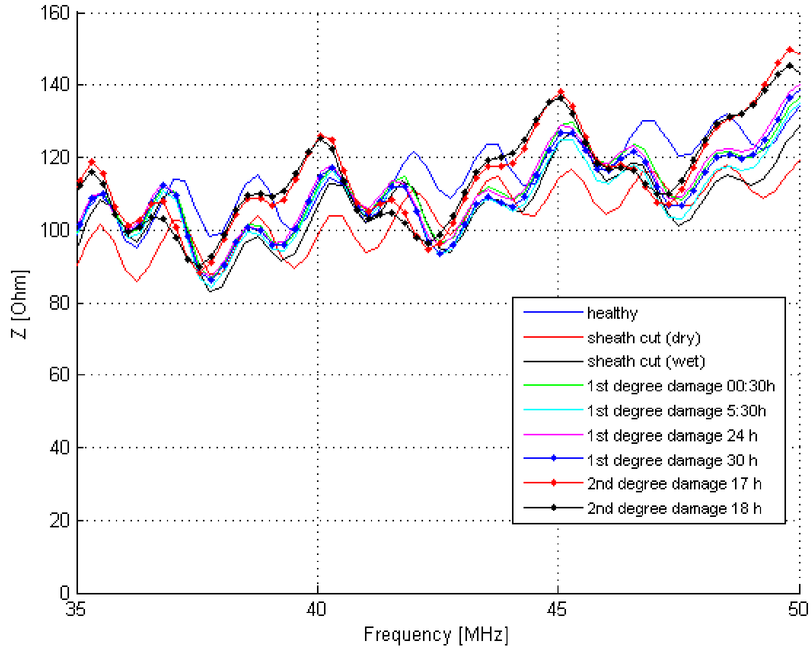


Fig 6.22. Phase-to-phase fault: AMCMK cable (L1-L2), from 35 MHz to 50 MHz.

In the upper range, Fig 6.22 shows how that second faulty stage, where two phases conductors are exposed is showing a behaviour similar to that presented by the AXMK cable, deforming continuous reflections showed by dry cases and also making some impedance variations regarding the first faulty state.

It can be said that phase to phase faults are more noticeable than phase to ground faults looking their impedance signature, but taking into account that now there are two phases involved in the damage.

6.4.3 Attenuation study

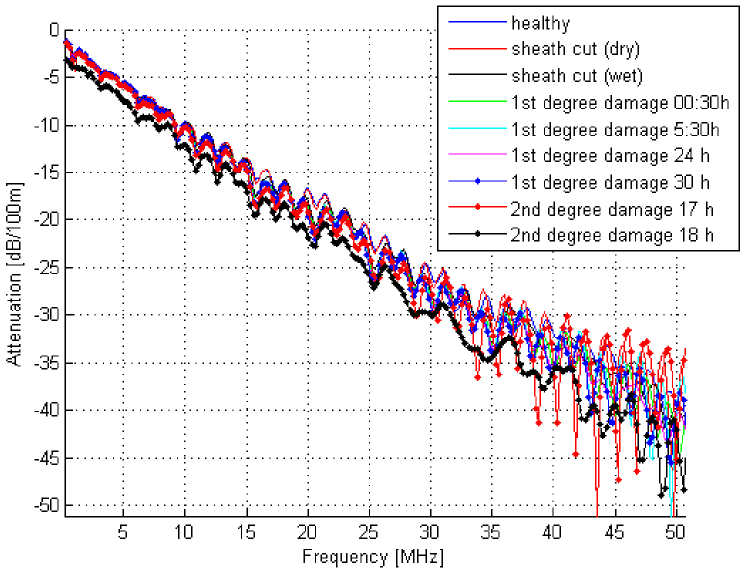


Fig. 6.23. Phase-to-phase fault: Attenuation curve for the AMCMK cable (L1-L2) up to 50 MHz.

Attenuation differences between healthy state and last damage faulty state are shown in the next table. They are three samples taken in the 20 MHz-30 MHz range, and a deviations of more than 4 dB can be seen.

Table 6.3. Attenuation difference samples from the healthy and the last 2nd degree state.

Frequency [MHz]		20	25	30
Attenuation (dB/100m)	Healthy – First stage	-16.87	-21.7	-25.5
	Δ	4.97	4.87	4.5
	2nd degree damage – Last stage	-21.84	-26.57	-30.05

Now there is an estimation of attenuation curves following the same procedure of fitting as in the previous fault type, and similar results are obtained.

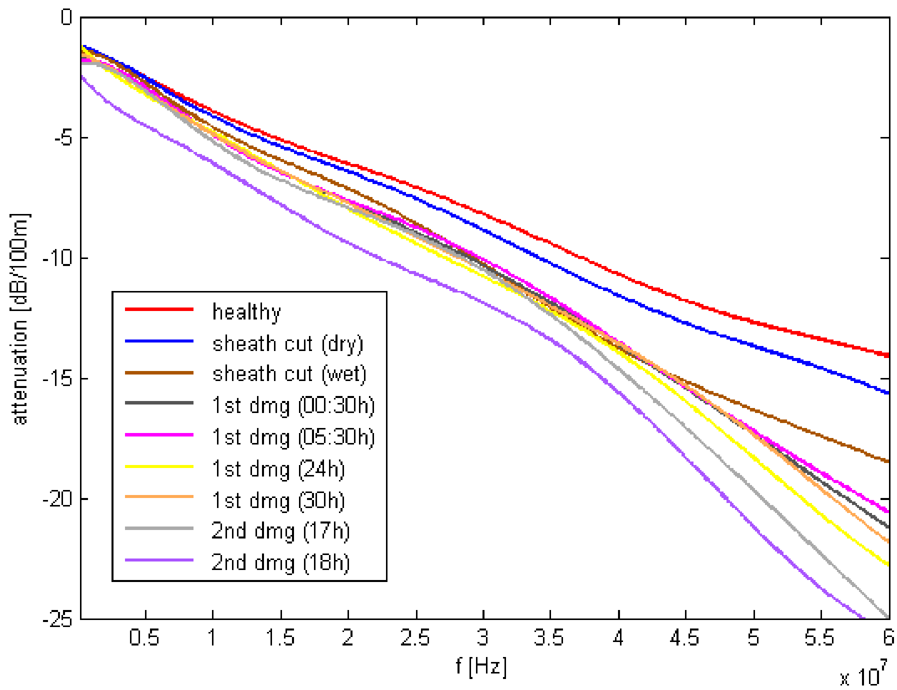


Fig. 6.24. Phase to phase case attenuation coefficient up to 60 MHz (AXMK cable, L1-L3).

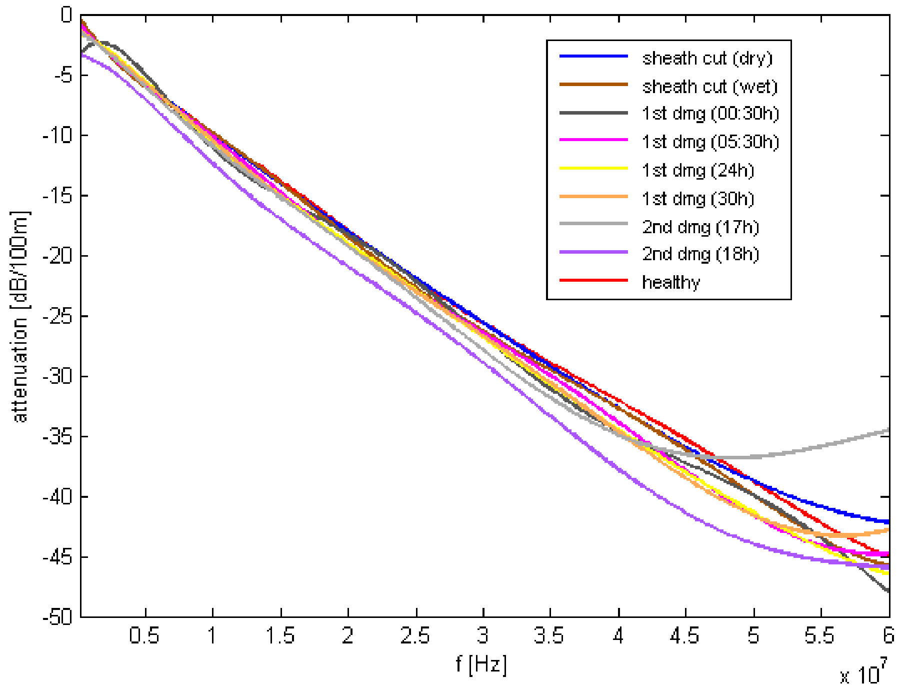


Fig. 6.25. Phase to phase case attenuation coefficient up to 60 MHz (AMCMK cable, L1-L3).

A comparison between phases is shown below for the AXMK cable. L1-L3 is presenting lower attenuation from 20 MHz than L1-PE in all cases. It has to be noted how healthy curves have a difference of 6 dB at 60 MHz, so each faulty curve should be referred to those attenuation levels calculated from the healthy state.

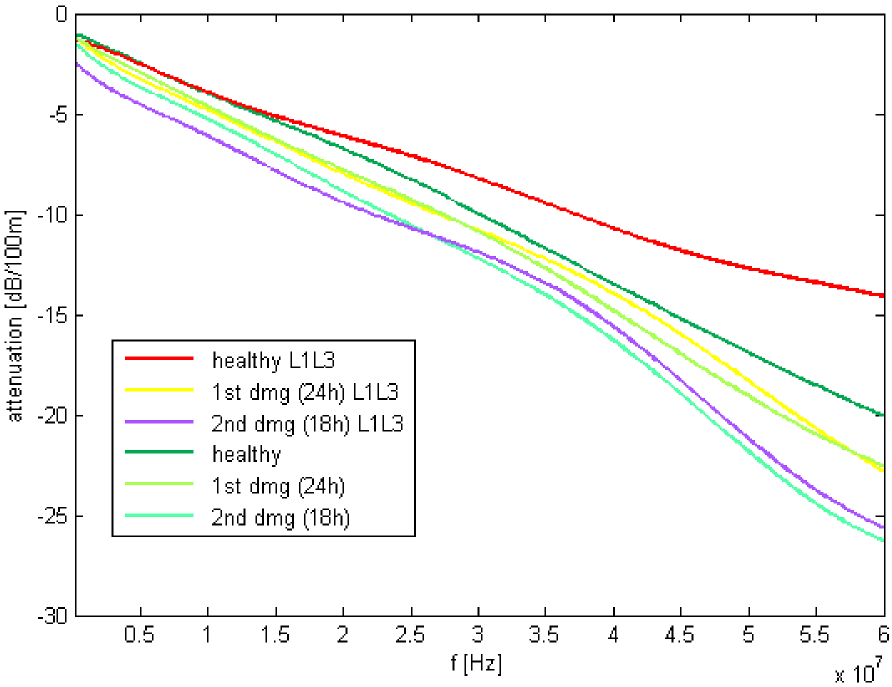


Fig. 6.26. Phase to phase attenuation comparison between L1-L3 and L1-PE up to 60 MHz (AXMK cable) for three different fault stages in each phase relation.

6.5 Long term measurements

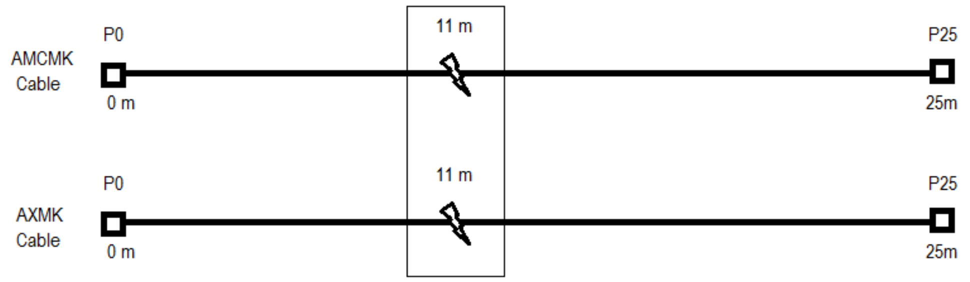
6.5.1 Setup

The next setup is similar to the setup of previous chapter measurements. Measurement procedure is the same but keeping only three fault degree states. The last fault stage is that one with the sheath removed and under the water. It is kept during a long period. Main purpose is to see the incidence of the moisture ingress on cores' insulation. A scheme of the fault placement can be seen in Fig. 6.27 with a 25 m long cable instead of the 50 m used in previous measurements.

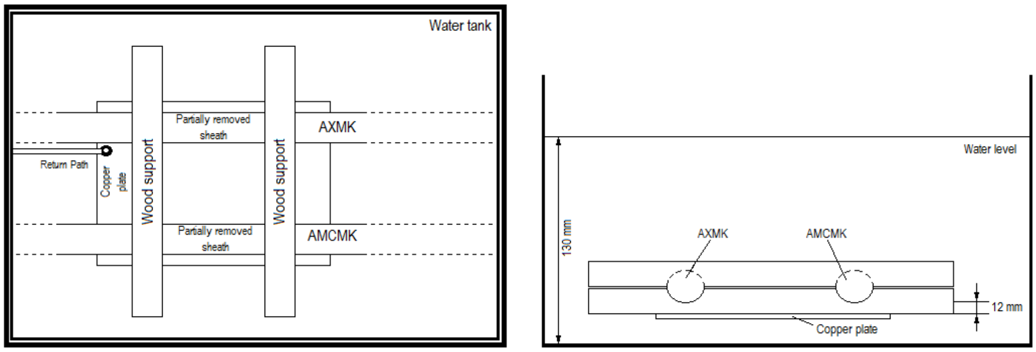
Table 6.4. Stages describing the long term measurements.

Stage	**Damage description**		**Hours**
	AXMK	**AMCMK**	
Healthy	-		-
Cut dry	Half of the sheath removed, dry environment		-
Sheath cut wet	Half of the sheath removed, wet environment		01:00h
			02:00h
			04:00h
			23:00h
			25:00h
			27:00h
			47:00h
			49:00h
			51:00h
			71:00h
			73:00h
			75:00h
			145:00h
			169:00h
			193:00h
			240:00h
			362:00h
			671:00h
			818:00h
			1035:00h
			1227:00h

As it can be seen in Table 6.4, a special effort is put in know about the temporal evolution of the fault, instead of the degree of damage.



(a)



(b)

(c)

Fig. 6.27. In (a), fault distance to P0 can be seen for both 25 meters long cables and (b) shows the disposition of the copper plate in the tank. (c) shows the water tank where the fault is placed for the long term measurements.

6.5.2 Measured input impedance

AXMK cable

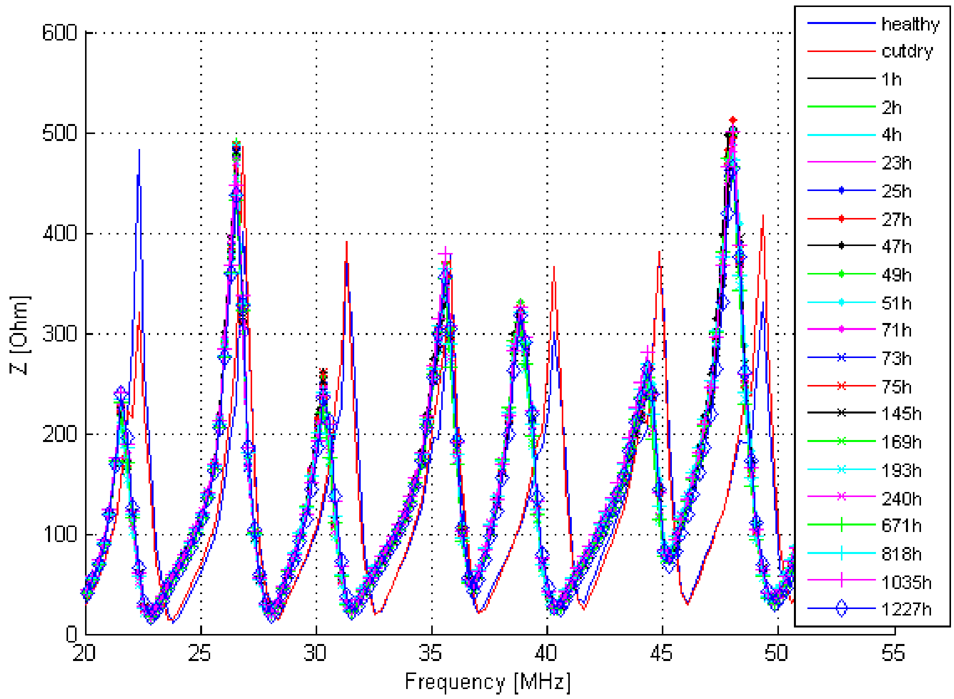


Fig. 6.28. AXMK cable (L1-PE), from 20 MHz to 50 MHz.

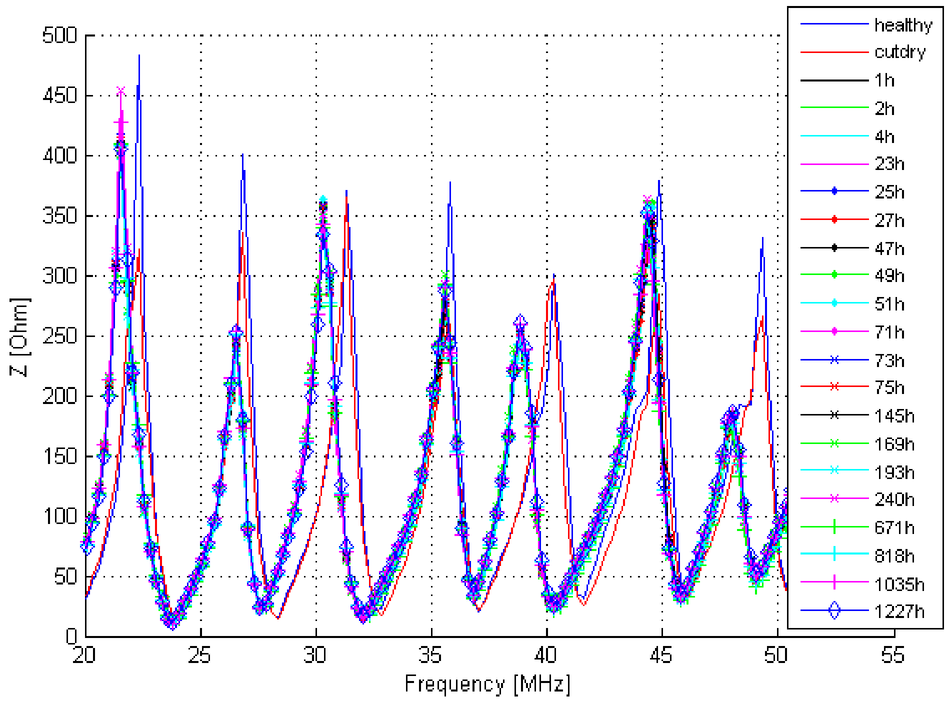


Fig. 6.29. AXMK cable (L1-PE), in the 20 MHz to 50 MHz range (from node P25 to node P0).

From the graphics above it can be seen how input impedance peaks are being shifted to lower frequencies. It is due to the increased capacitance. Those peaks behaviour can be compared with a parallel resonant circuit, where attenuation will be low at the resonance frequencies and over and under them that attenuation will be increased.

Results from changing the way of the communication are showed in figures above. Peaks' positions in the healthy/dry state remain the same but it is shown how with the water under the sheath peaks amplitude is changing, corresponding lower peaks in one way with higher peaks in the other measurement way.

Regarding higher frequencies, there is the same behaviour as it was observed in previous measurements. One of the points of interest of this study was check if the fault could be making a constant degradation of the channel, with several measurements on first hours of the setup. Because no changes could be appreciated once the water penetrated through the sheath, measurements were done increasing time sampling.

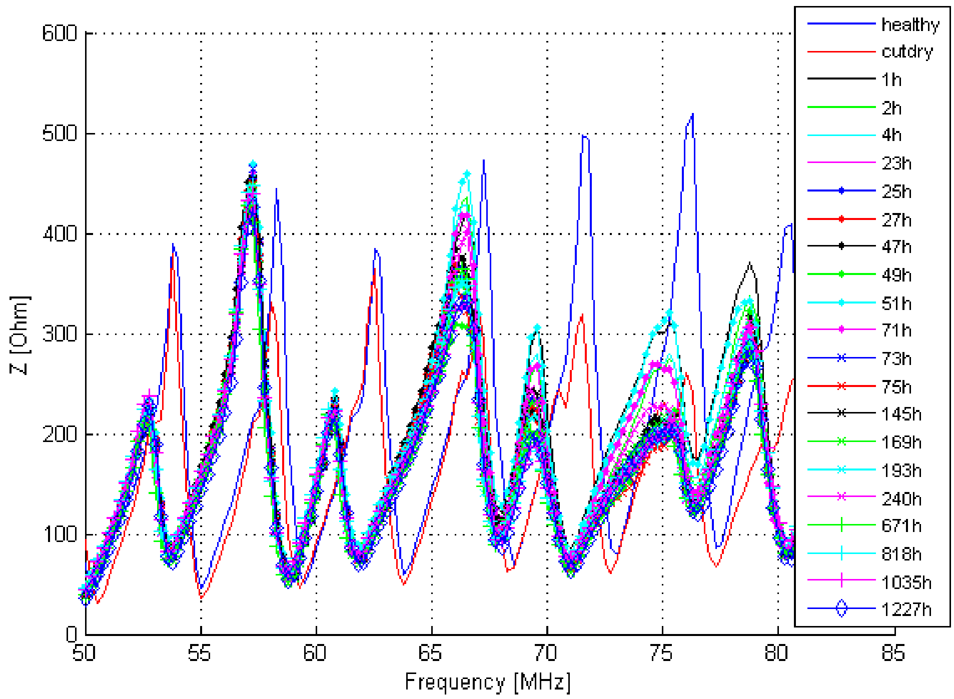


Fig. 6.30. AXMK cable (L1-PE), from 50 MHz to 80 MHz.

Results are not giving a proportional degradation that could be seen as a constant impedance variation. They remain at the same impedance levels, oscillating in a range of few Ohms but keeping the signal response which is affected by water ingress.

AMCMK cable

Regarding the length of this measured cable, contrast between faulty cases and healthy ones is now higher. It can be seen on figures below, where deviations are now bigger than in the 50 meters long cable.

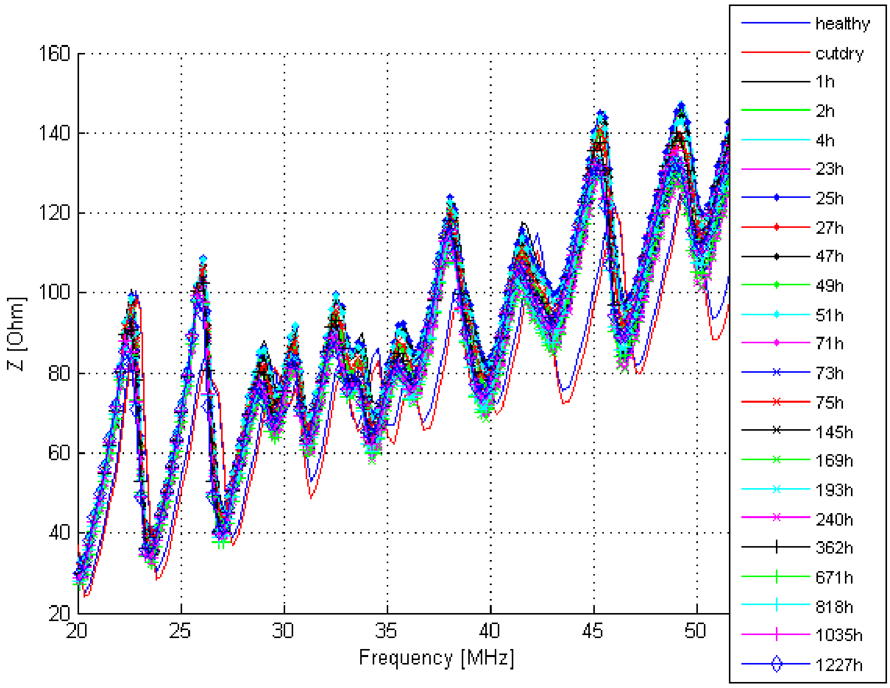


Fig. 6.31. AMCMK cable (L1-PE), from 20 MHz to 50 MHz.

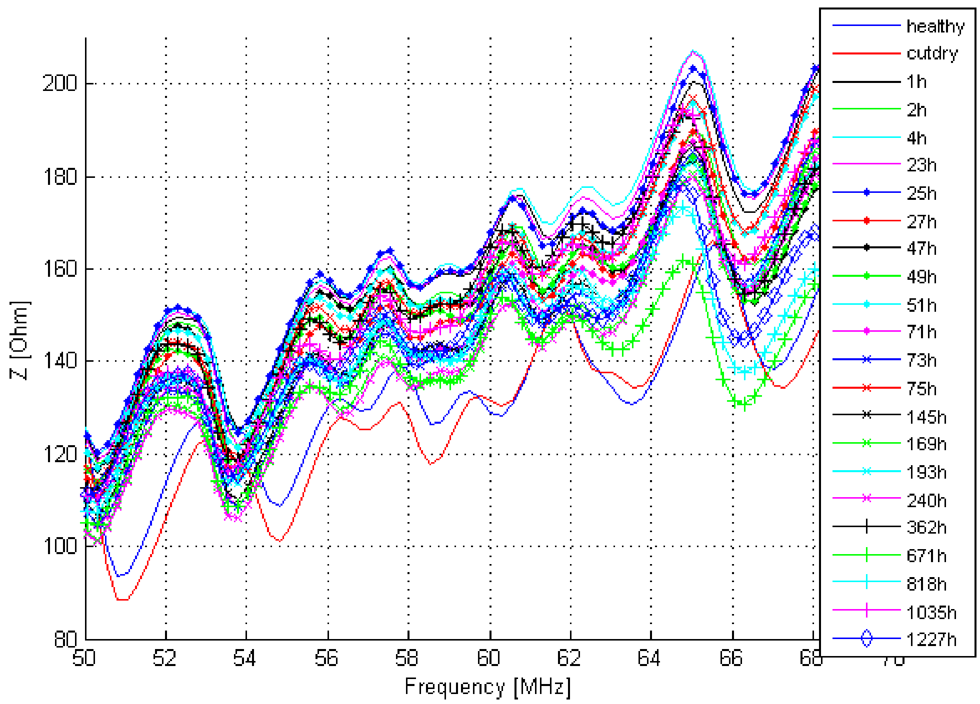


Fig. 6.32. AMCMK cable (L1-PE), from 50 MHz to 68 MHz.

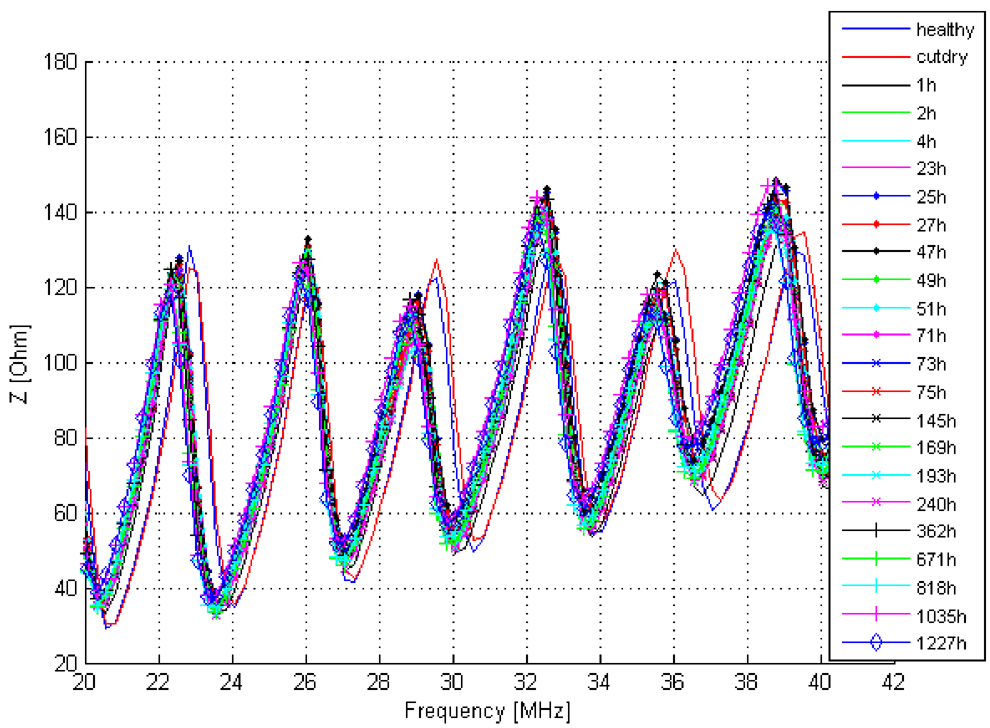


Fig. 6.33. AMCMK cable (L1-L2), from 20 MHz to 40 MHz.

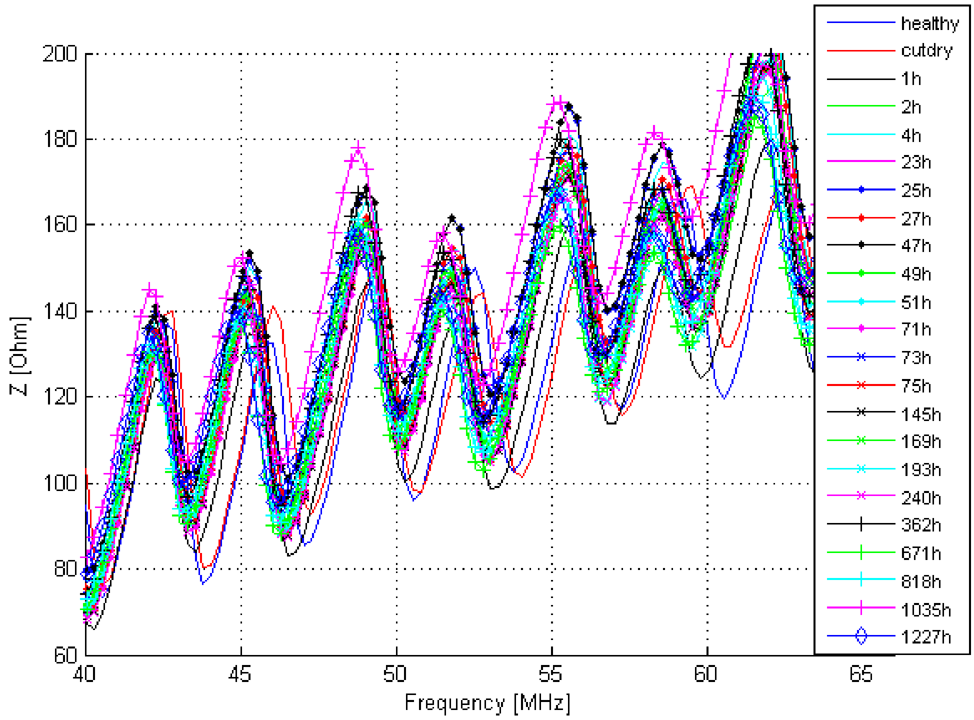


Fig. 6.34. AMCMK cable (L1-L2), from 40 MHz to 64 MHz.

6.5.3 Insulation degradation study

All tests performed to the cable contemplating if there will be leaking currents were showing no damage on the insulation. After almost two months of continuous measurements where voltage was applied charging both cables no currents were detected.

Furthermore, insulation resistance tests were giving proper impedance values, assuring healthy cable state.

6.6 Branched scheme

6.6.1 Setup

In order to get closer with a real power line grid for fault analysis and detection, a grid was built. It is only composed by two branches, which implies two T-joints, following the distribution that can be seen in Fig. 6.35. There will be a fault following the same disposition as in previous chapters, placed in a water tank with the copper plate. For this configuration only AXMK cable was chosen because of its better performance in terms of attenuation.

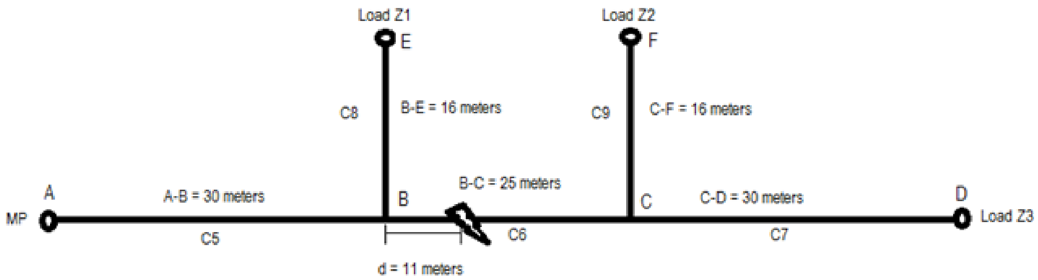


Fig. 6.35. Branched scheme representing a simple grid.

In order to be able to build a simulation scheme which could be used to obtain the signature of the network, every cable single-segment's input impedance is measured. It is done between all the possible paths, so the transmission path will be characterized for every combination. This is related to the grid fingerprint seen in chapter 4.3.3, which will be the base to apply the fault location analysis.

(a) (b)

Fig. 6.36. Joints in nodes B and C of the branched scheme.

Input impedance measurements were also performed in the whole scheme, but taking as the main path for the study the path between points A and D, following the tags in Fig. 6.35.

Table 6.5. Stages followed in the branched scheme measurements for the AXMK cable

Stage	Damage description	Hours
Healthy	-	-
Sheath cut (dry)	150 mm long of half of the sheath removed	-
Sheath cut	150 mm long of half of the sheath removed, under water	01:00 h
		20:00 h

For this configuration, gain-phase measurements were also carried out. The aim of this analysis is to know how time-domain transmission for fault location purposes is working with the changes, which have been seen in the impedance results. This is done with the theory background seen in chapter 4.4.2. It has to be taken into account that the necessary gain-phase frequency measurements are performed with the HP 4194A analyser that is been used on the impedance analysis. To take the information a frequency sweep is supplied on the whole range up to 100 MHz. First, with a 25 meters long cable segment, a comparison of both healthy and faulty states will be shown. Then an analysis of the time-response in the grid is made, and it can be seen how the complexity of the analysis is increased.

The grid is symmetrical, but it is not when the fault appears. This consideration points how the transmission path has to be identical in both ways when the cable is healthy and how the channel is changing depending on the way when there is a fault. Four fault stages are studied as is shown in Table 6.5.

6.6.2 Impedance analysis of the transmission path

Only the main path (nodes A to D) will be shown here, comparing the four different states in the impedance ranges which were selected in previous section as the more suitable for changes identification. It can be seen in the graphics how both wet and dry conditions are again giving different results, seeing how the fault can be detected when the water starts penetrating under the sheath.

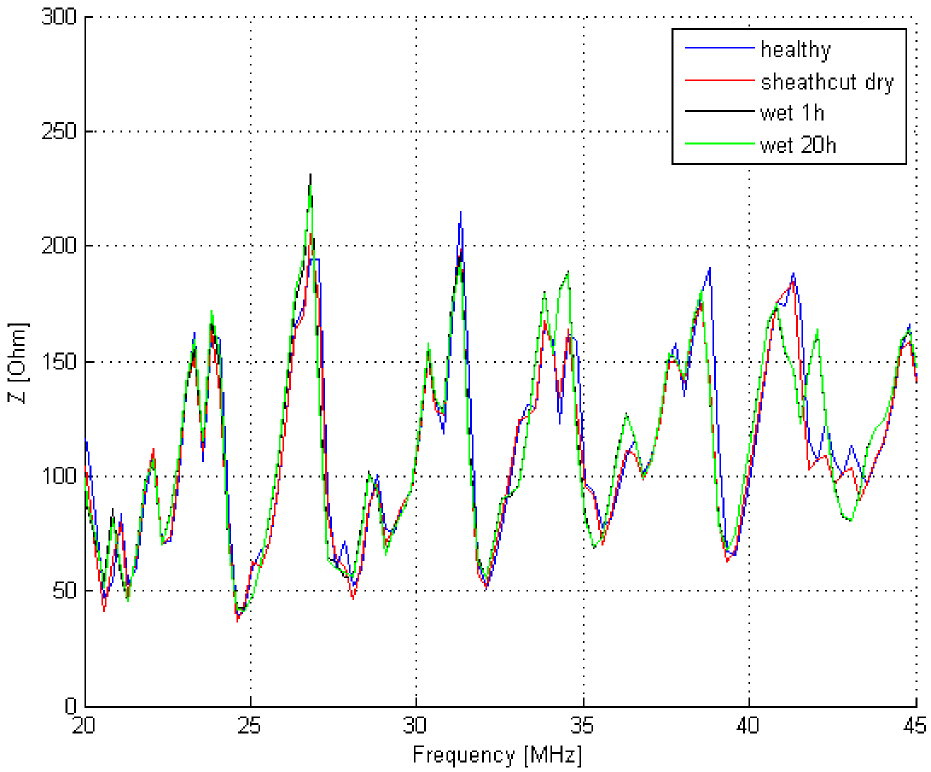


Fig. 6.37. Input impedance for L1-PE in the branched scheme, path A –> D (20 – 45 MHz).

Differences are not comparable to single segments results, because the faulty segment contribution now is subordinated to the rest of contributions. But there are still some frequencies where the changes are noticeable, presenting different behaviours (capacitive or inductive) depending on the presence of water under the sheath. Table 6.6 shows the main impedance differences with their respective frequencies, which are presenting the higher visual differences regarding Fig. 6.38 and Fig. 6.39.

Table 6.6. Input impedance main differences between states (L1-PE and A -> D path)

Frequency [MHz]	42	43	50	51	56	57	58
ΔZ [Ω]	57	32	41	27	38	34	25

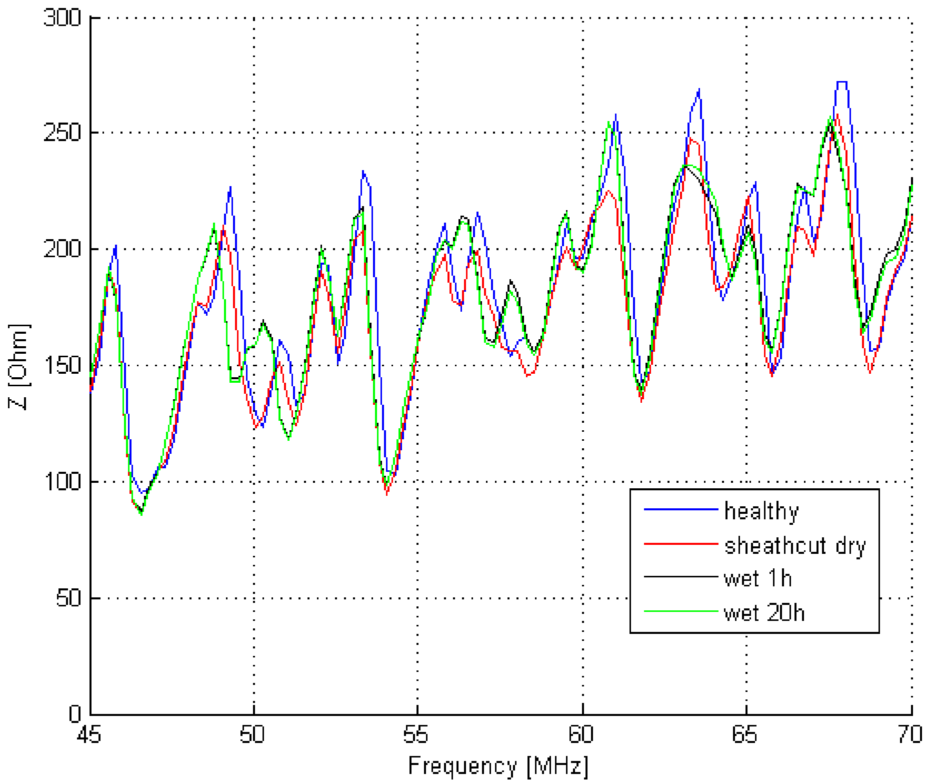


Fig. 6.38. Input impedance for L1-PE in the branched scheme, path A –> D (45 – 70 MHz).

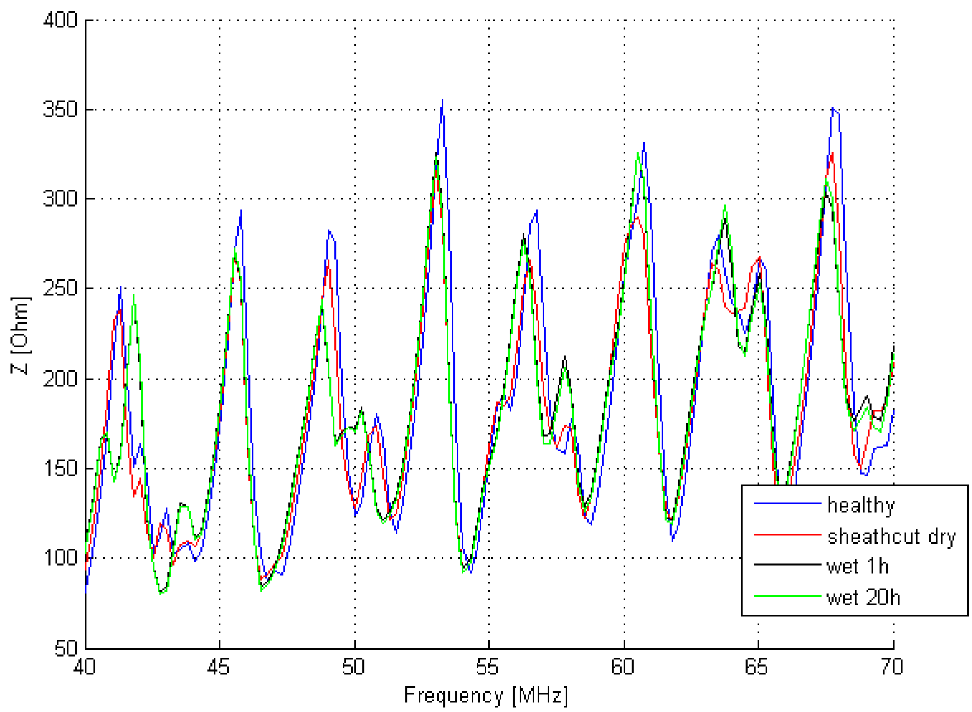


Fig. 6.39. Input impedance for L1-L3 in the branched scheme, path A –> D (45 – 70 MHz).

6.6.3 Gain and phase measurements

Single segment evaluation

Now the time-domain analysis of the grid is performed. The first step is to know its capabilities for a 25 meters long single segment. The pulse will be reaching the receiver after 25 meters, and there will be a reflection, then it will come back to the transmitter and will be reflected again. So the first reflection coming from the far end represented by the transmitter will be reaching the receiver after 75 meters. This is the range of interest, where intermediate reflections are clear to see. After that, there is a similar effect on the received signal but with the corresponding attenuation.

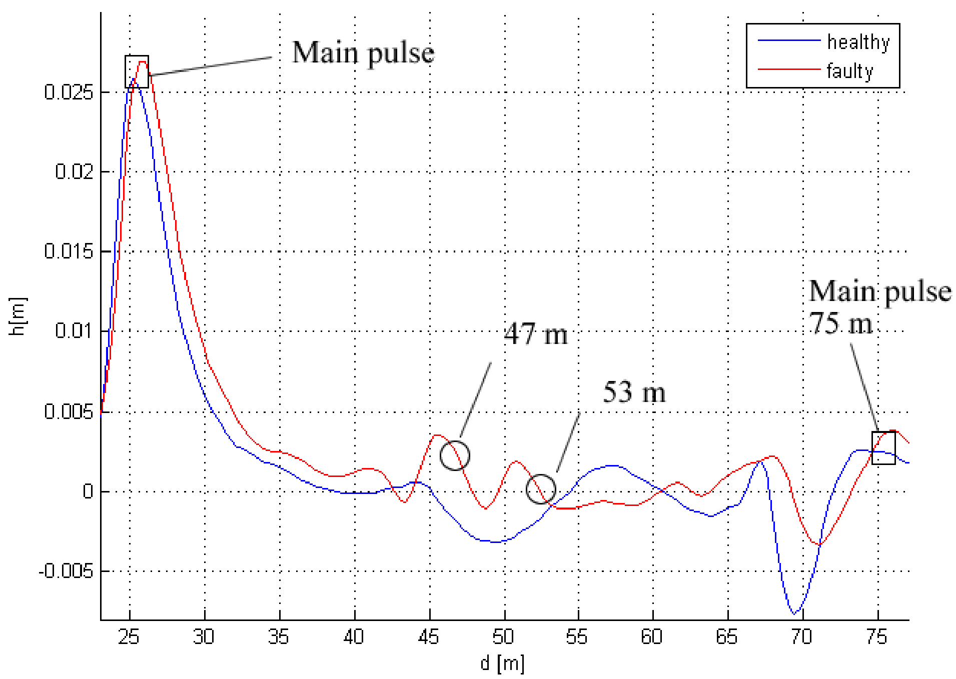


Fig. 6.40. Time-domain transmitted pulse in both healthy and faulty (sheath removed and wet) states (L1-PE measured) in a 25 meters long AXMK cable.

The faulty state to be compared with is characterized by a fault at 11 meters from the start of the cable (port 0). That fault is the same as that caused on long term measurements, with the sheath removed (water penetrating) and without damage on conductor insulation. Then, main reflections will be placed at 47 and 53 meters, as it can be seen in Fig. 6.37. In this case accuracy in the distance can be affected by the connectors employed to attach the gain-phase analyser to the cable ends, but it is shown how the fault affecting system's impedance, is causing reflections that can be observed and situated. Velocity of propagation of the cable is an approximation of the nominal velocity characteristic of the cable due to connections and intermediate elements on measurements, being in this case .

It should be noted how due to the capillary effect, water is not only in the cable section under the water (0,6 meters) but it is being spread along few meters in both ways. So, in order to evaluate the location of the fault has to be mentioned how reflections can be coming also from those water ingress limits. It is not done here in order to simplify measurements and because these contributions use to be less noticeable than those on the faulty point. Moreover, that capillary effect scope can vary depending on the physical distribution of underground cables.

Once it is checked how the fault can be located in a simple case, further complexity can be considered.

Fault location with power line branches

If the number of branches is increased, the number of possible paths for the signal will be also increased. Discontinuities in those paths or mismatched ends will be causing multiple reflections. That is called the multipath effect, always present in unguided transmission mediums for wireless communications but also present in some guided schemes where multiple paths are present. Because it is usual in LV distribution, those effects have to been taken into account and fault location based in pulse echoes is not an exception. Those echoes coming from different reflections in the network will be growing as the number of discontinuities is increased.

In the scheme proposed and considering the main path, gain-phase measurements were taken with an open circuit on branches ends, so all the incident signal will be reflected back. First pulse reaches the receiver at the 85 meters, following the direct path. Symmetrical view of the grid adds the effect of how both secondary pulses from branches E and F are reaching the receiver at the same time in 117 meters, so the sum of their contributions in the far end is even bigger than the contribution of the main primary pulse. The distance range of interest is covering from 85 meters to 255 meters corresponding with the first pulse received and with the primary pulse first reflection through the main path, respectively.

A lattice diagram showing all the reflections from the network in that interval for the healthy scheme is presented in Fig. 6.41. Every ray touching the final line is a pulse with more or less amplitude in the time-domain analysis. There are situations where pulses are arriving together. That is contributing to receive the signal with higher amplitudes in those locations.

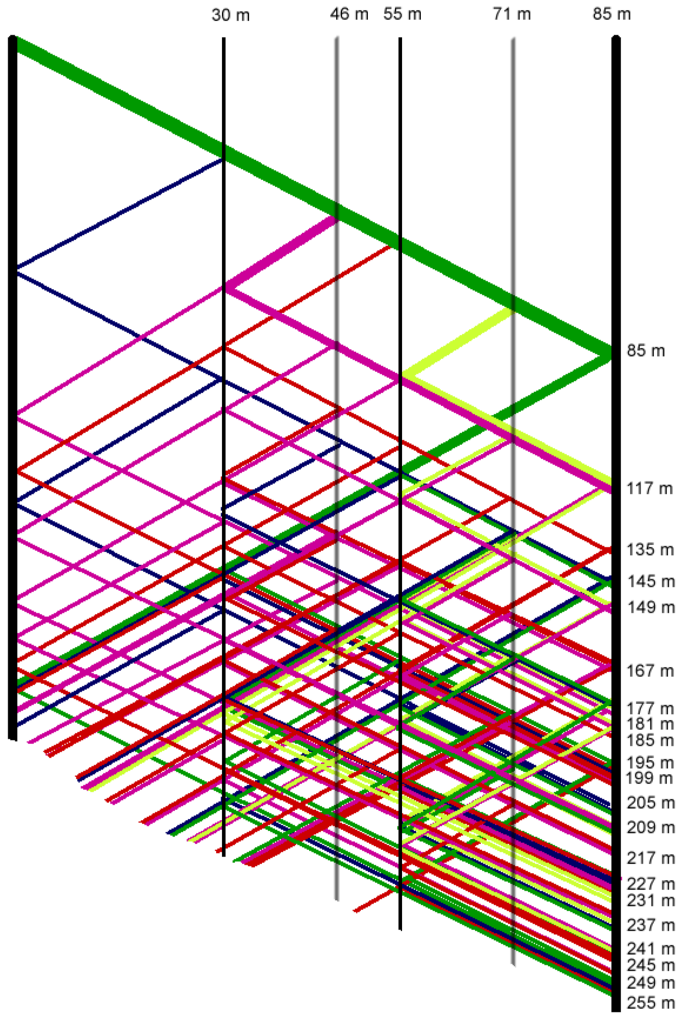


Fig. 6.41. Lattice diagram of the branched scheme without the fault.

It can be seen in the Fig. 6.42, there are several differences between both dry and wet cases, but they are not high enough to ensure the reliability of traditional fault location methods, claiming for improvements on attenuation and impedance changes detection. This is the idea presented in [58], where small impedance changes are not very clearly detected with TDR and is necessary the use of auto-correlation-based techniques. So, if changes can be seen with this time analysis, with the improved techniques, facing the attenuation problem, they will be taken more accurately and differences will be higher.

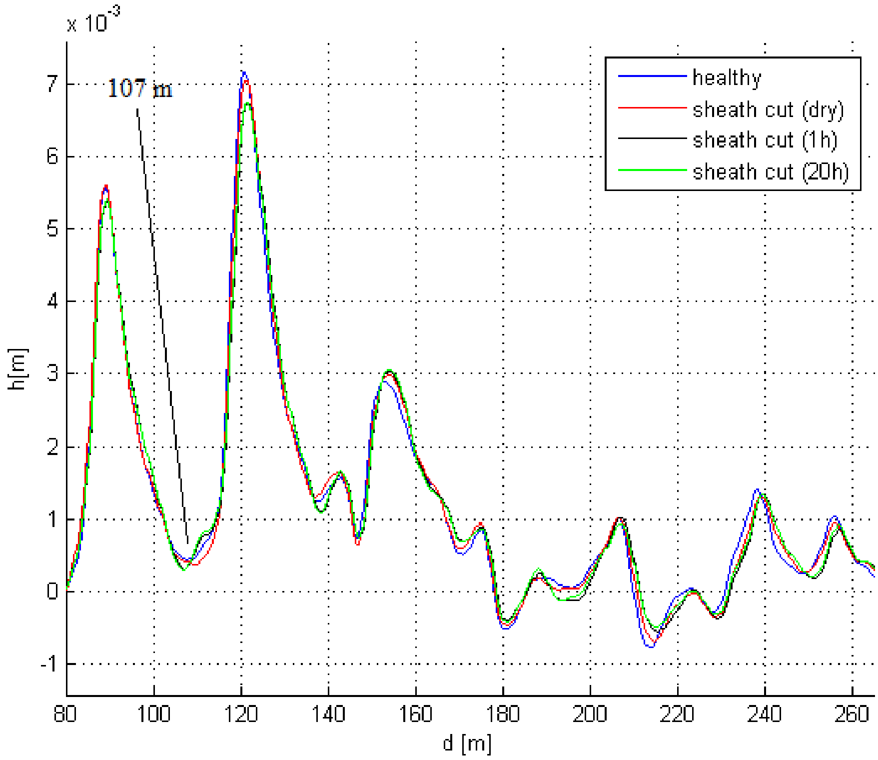


Fig. 6.42. Time domain transmitted pulse in the branched scheme (phases L1-L3) comparison between healthy state and next stages. First fault-reflection appearance ( ).

In a more detailed view of the previous figure, differences caused by the fault can be seen for the next grid reflections, as it is shown in Fig. 6.43. It has to be mentioned that there is a small delay between both situations and how the mis-match represented by the fault is causing a small amplitude penalization.

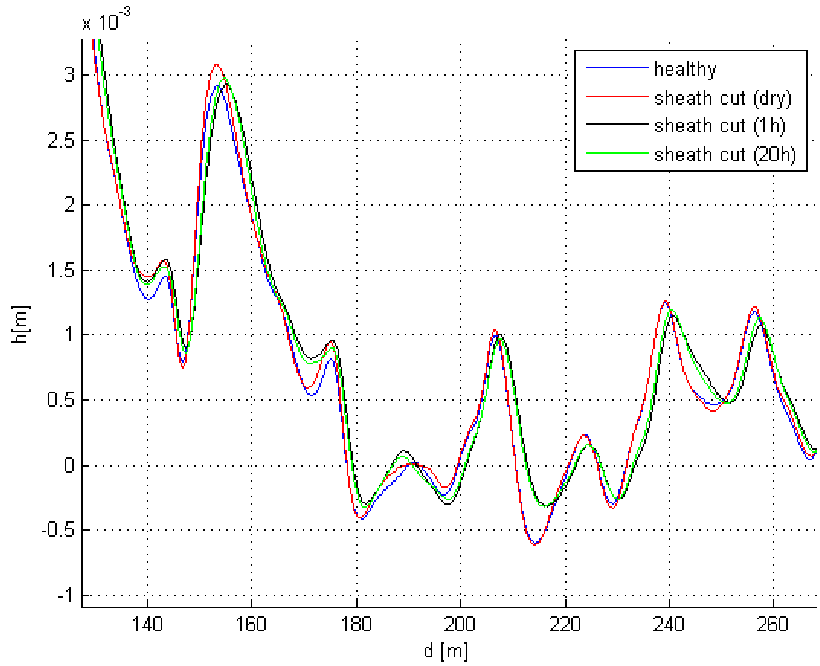


Fig. 6.43. Differences between wet and dry fault for the last reflections (L1-PE).

All changes between dry and wet states could be seen for the AXMK cable with more accuracy if the attenuation effect is reduced and if the noise can be faced by new improvements in classical time domain analysis.

7 Conclusions

In this work a study about communications channel behaviour in LV power lines when there is a fault present was done. Distribution power lines act and can be seen and characterized as transmission lines, so their behaviour will be conditioning the reliability of communications. Through an exhaustive analysis about how faults apparition works and how to detect them, the main capabilities of new fault location methods where critically selected. One of the main problems to be faced is regarding attenuation suffered in the system. In fault location, it is also a disadvantage when faults represented by low impedance variations have to be located.

Once the fault location mechanisms were known, an evaluation of the communications channel was performed simulating different fault stages to see how changes in the fault are affecting the channel. That characterization was performed attending high frequencies, in a range were the faults could be detected but attenuation losses can be affordable. The main analysis was done using input impedance measurements of the lines, represented by AXMK and AMCMK cables commonly used in distribution lines. Using these measurements and using line parameters analysis, cables were characterized in each faulty stage.

The main conclusion about the analysis is how the fault can be detected when moisture is present under the sheath. In this case, moisture ingress was simulated taken into account the worse scenario, where cables are completely submerged in water. There were performed measurements when the cable is dry and many of them with water under the sheath and increasing gradually the damage degree to see how it affects cable behaviour. Different faulty stages were giving almost the same results once the water ingress is present, but there are clear changes in impedance frequency response signature regarding the healthy state of the cable. Cables were even in a faulty state where insulation of two phases was partially removed in a small section, but they continue working anyway. For this case attenuation degradation, that will be affecting communications performance, is more than 20 dB/100m regarding the healthy cable and when frequencies are close to 60 MHz.

An analysis considering the water ingress under the insulation was also done, leaving cables under water several hundreds of hours. Obtained results are not showing more differences than those seen for previous measurements. It was also observed how leaking currents have a strong dependence on the quantity of impurities composing the moisture, which is affecting the fault, and also in general about fault surroundings.

Finally, time-domain signature of channel changes, and how fault location could be detected by pulse echo are studied. For that purposes a simple branched scheme/grid was built, and a fault was simulated to compare both system healthy and faulty signatures. Results were showing how multipath effect is complicating the analysis but changes can be detected. It is suggested how new fault location techniques can be facing attenuation problems and showing more clear those faulty situations, taking advantage of autocorrelation functions.

About the implementation in real LV scenarios few things can be stated. Firstly, the impedance changes detection could be enough from the start point where the water is present under the sheath. Detection of impedance changes has not to be done immediately because it was proved how cables can work during long periods even under those faulty circumstances. This means that there is not necessary real time monitoring so measurements can be done following patterns of several minutes of even hours. The reliability of the system will be conditioned by the capability to make an accurate model of the channel in simulation. Once it is done, new fault detection techniques can be tested and implemented to know if there is a fault.

7.1 Future work

Three important related topics can be following this study. The first one is how to get a grid signature, a fingerprint, which could be simulated knowing cable characteristics. This fingerprint will be representing the condition of the healthy cable, and it could be used in simulation to make fault location analysis. A study using lumped components model was started to simulate an already known grid structure using software, getting then that fingerprint.

The second stage is linked with the development of the line checking process. That implies a transmitter in substations sending a signal using the frequency band proposed, and the receivers recording what they are getting and sending it back to the substation. Furthermore, information about loads in that end should be sent back to the substation.

A third step is how to compare a simulated healthy signature, applied over the healthy cable by using software, with the signal recorded by the receivers at customer's end. That comparison implies signal treatment to see if there are changes, which can be representing a faulty state.

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Appendix I. Visual description of fault stages

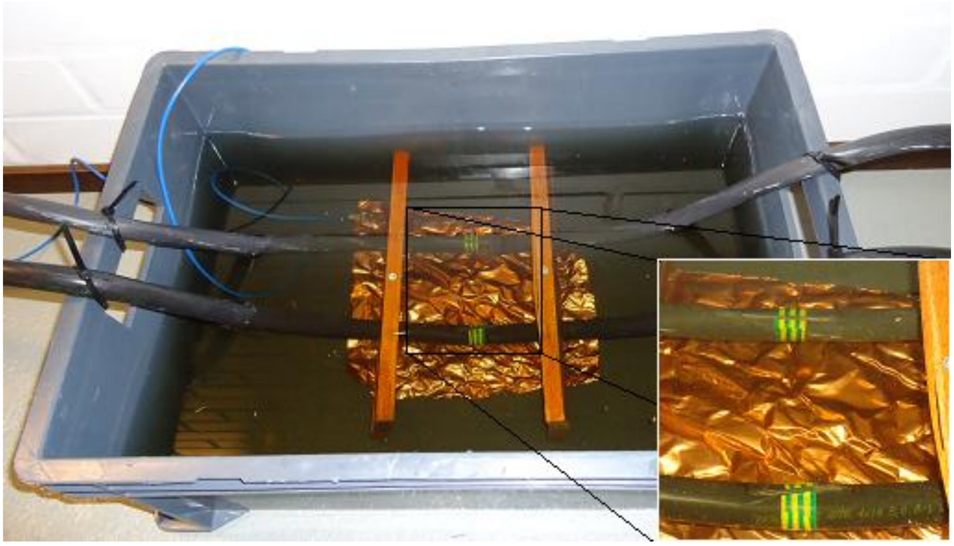
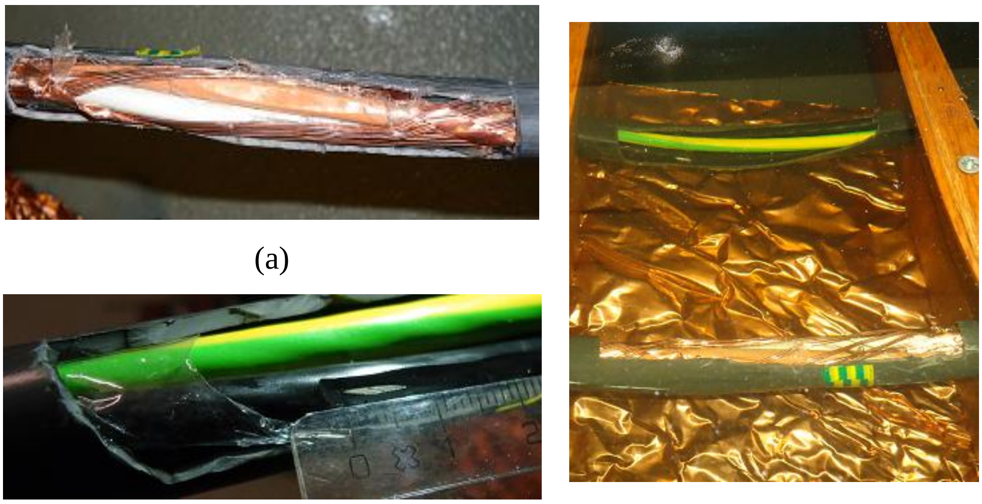


Fig. API.1. 50 mm long cut in the sheath. Cables submerged in water. A slow water penetration is expected.



(a)

(b)

(c)

Fig. API.2. First degree phase-to-ground fault.

(a) (b)

Fig. API.3. Second degree phase-to-ground fault: (a) Damage in AXMK L1 phase (b) Cables placed in the structure to be submerged.

(a)

(b)

Fig. API.4. Third degree fault affecting L1 phase in the AXMK (a) and the AMCMK (b) cables (phase-to-ground fault).

(a)

(b)

Fig. API.5. First degree phase-to-phase faults for the AXMK (a) and the AMCMK (b) cable.

(a)

(b)

Fig. API.6. Second degree faulty state (a) and (b) pictures showing AXMK L1 and L3 phases and AMCMK L1 and L2 phases respectively.

Appendix II. Input impedance analysis

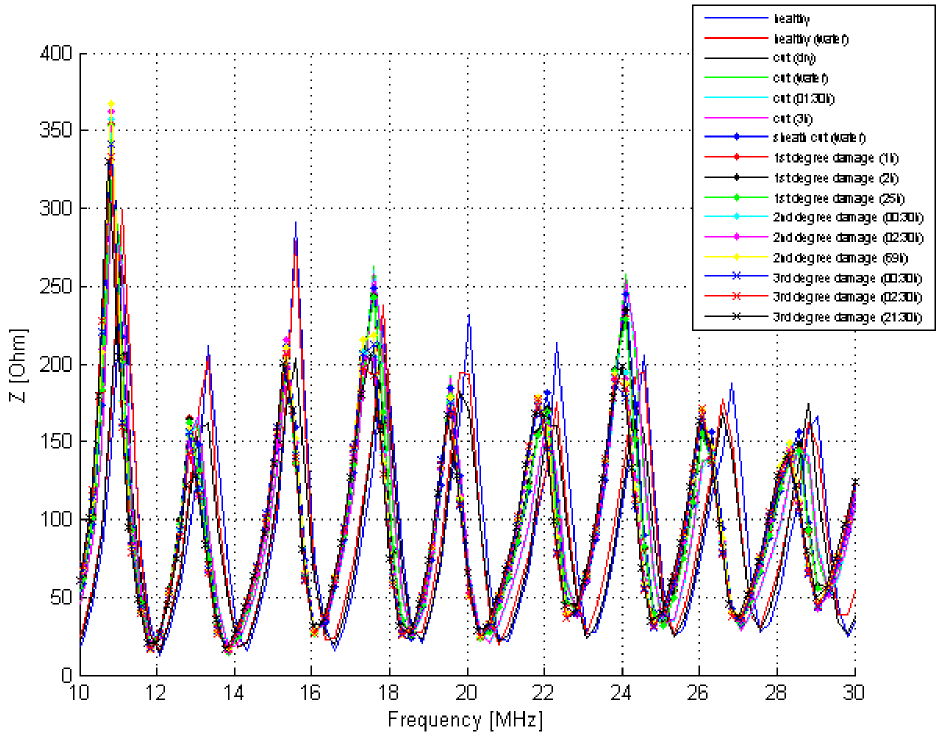


Fig. APII.1. Phase-to-ground fault: AXMK cable (L1-PE), from 10 MHz to 30 MHz.

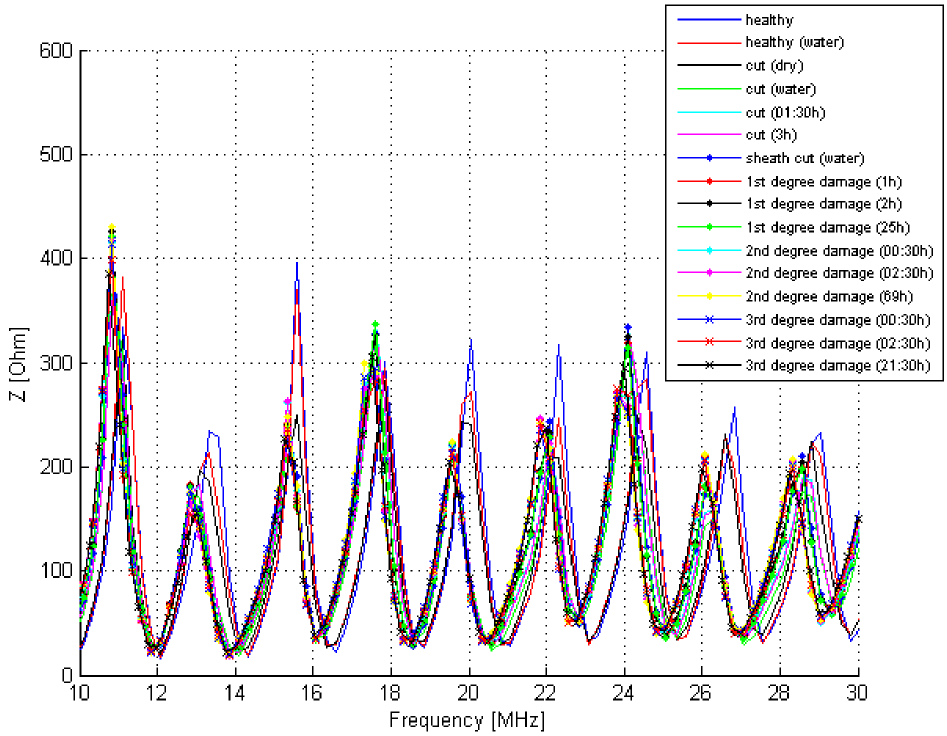


Fig. APII.2. Phase-to-ground fault: AXMK cable (L1-L3), from 10 MHz to 30 MHz.

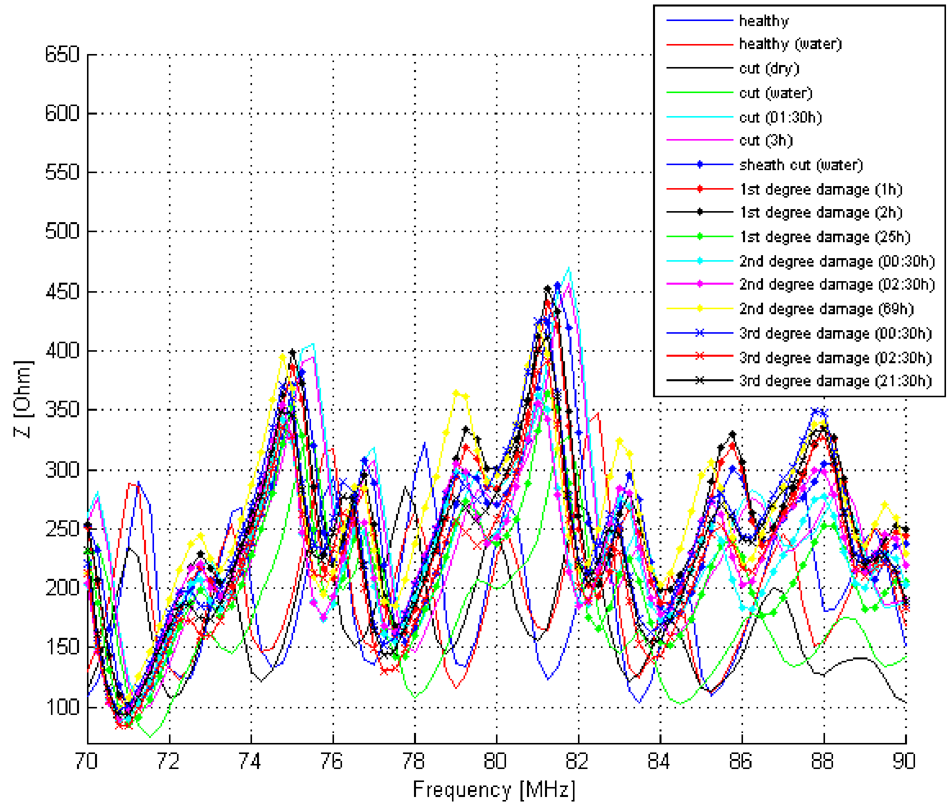


Fig. APII.3. Phase-to-ground fault: AXMK cable (L1-L3), from 70 MHz to 90 MHz.

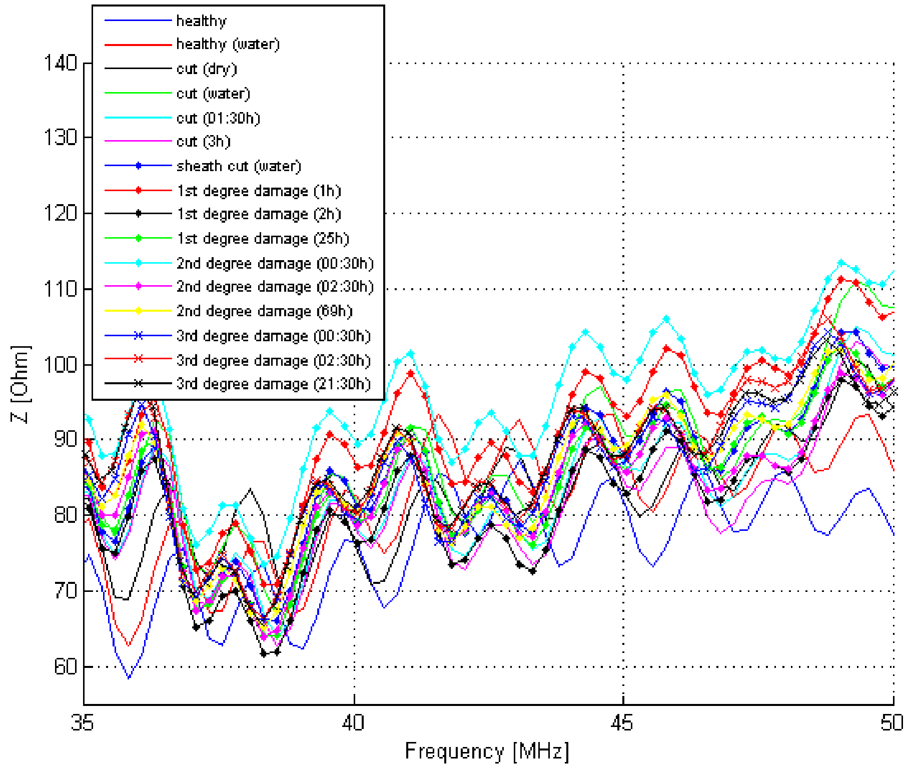


Fig. APII.4. Phase-to-phase fault: AMCMK cable (L1-L2), from 35 MHz to 50 MHz.

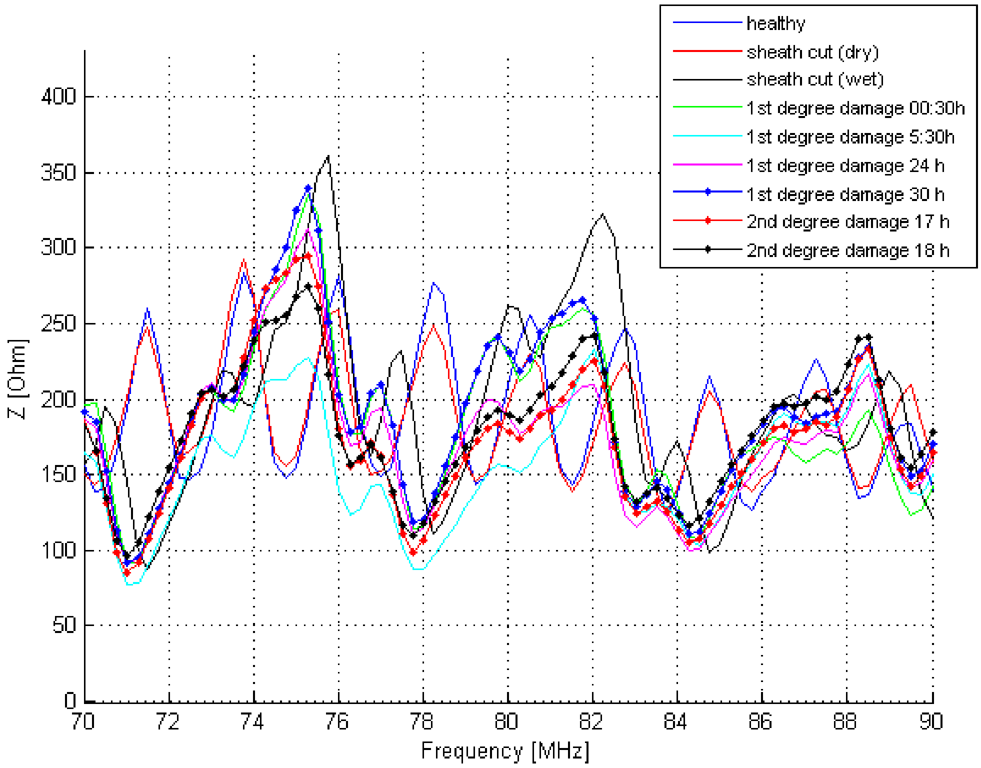


Fig. APII.0.5. Phase-to-phase fault: AXMK cable (L1-PE), from 70 MHz to 90 MHz.

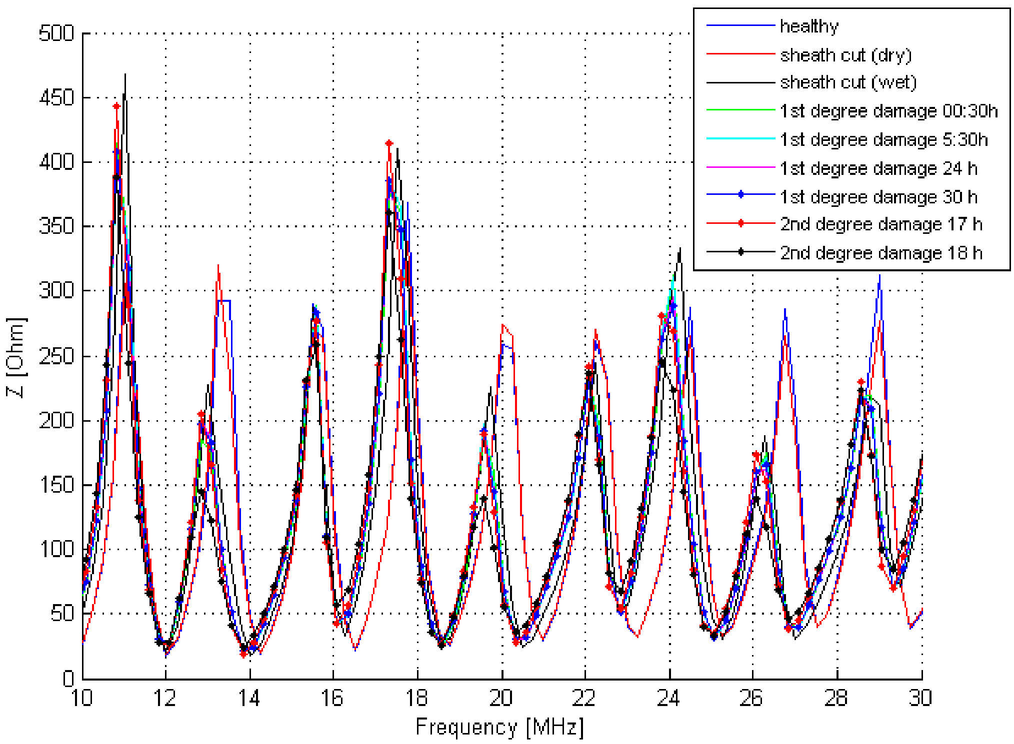


Fig. APII.0.6. Phase-to-phase fault: AXMK cable (L1-L3), from 10 MHz to 30 MHz.

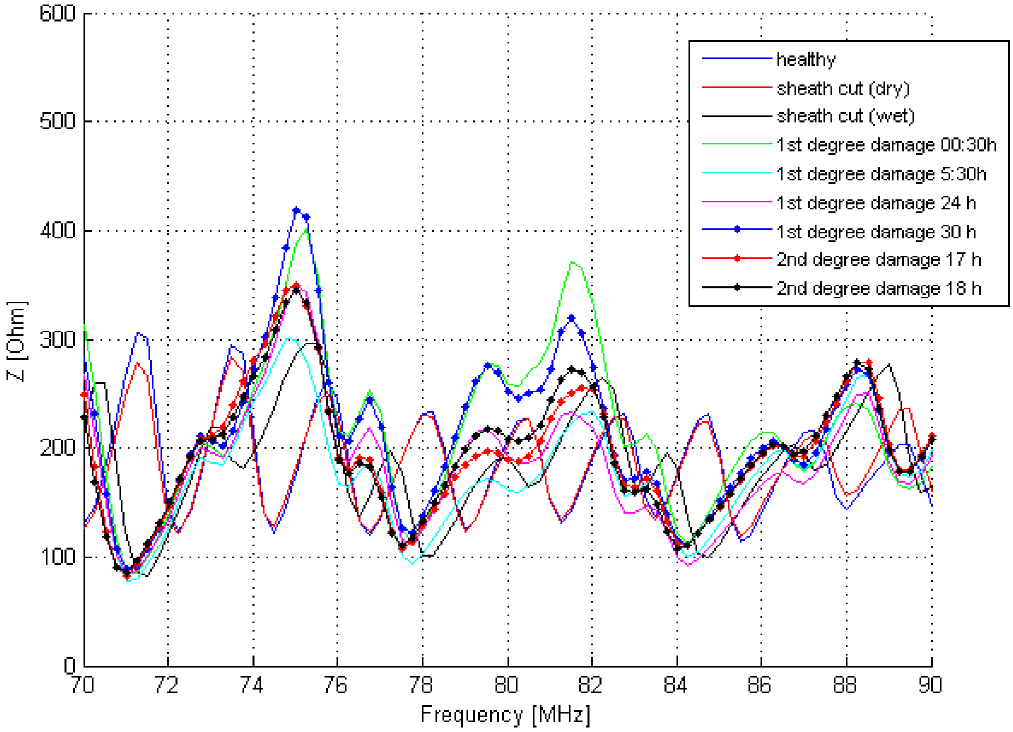


Fig. APII.0.7. Phase-to-phase fault: AXMK cable (L1-L3), from 70 MHz to 90 MHz.

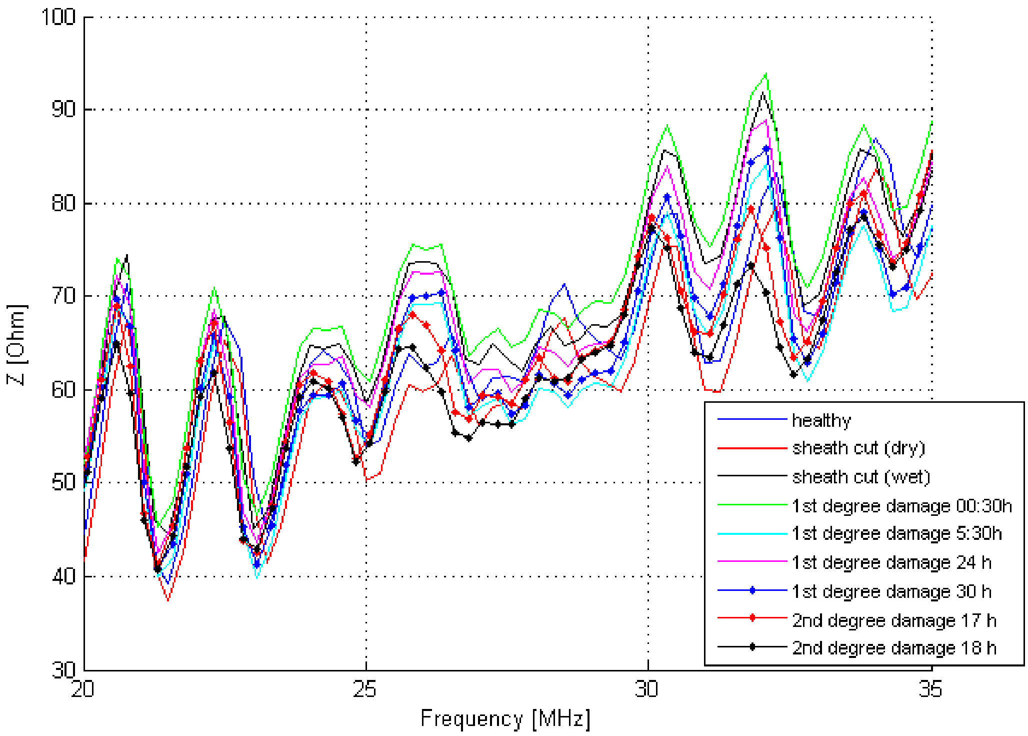


Fig. APII.0.8. Phase-to-phase fault: AMCMK cable (L1-PE), from 20 MHz to 35 MHz.

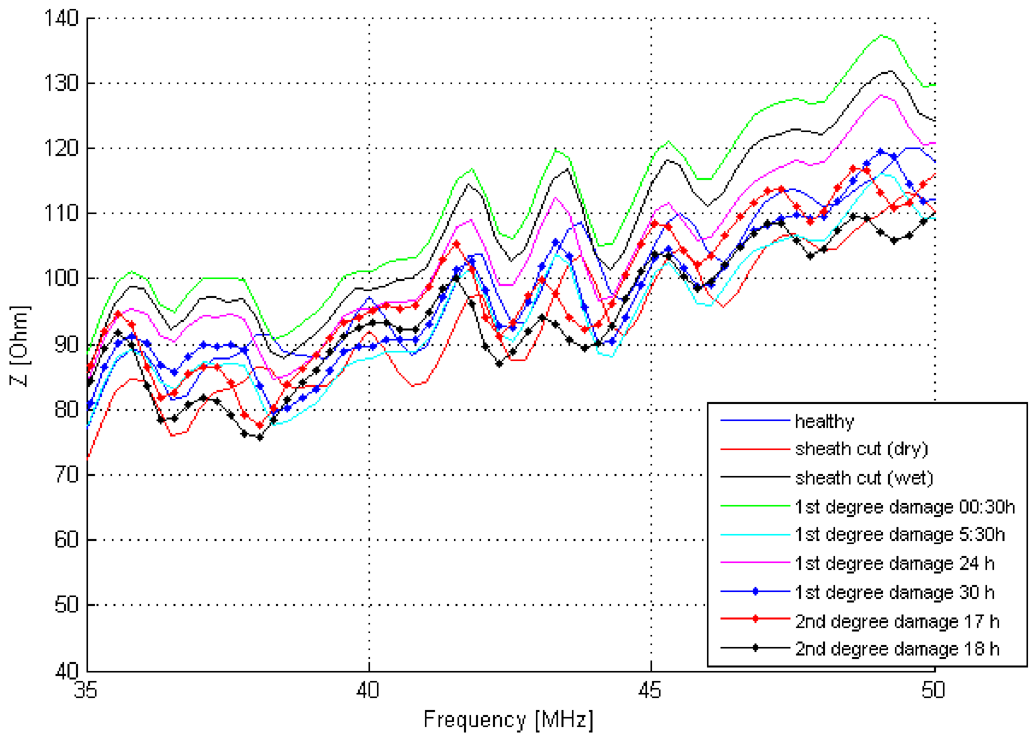


Fig. APII.0.9. Phase-to-phase fault: AMCMK cable (L1-PE), from 35 MHz to 50 MHz.

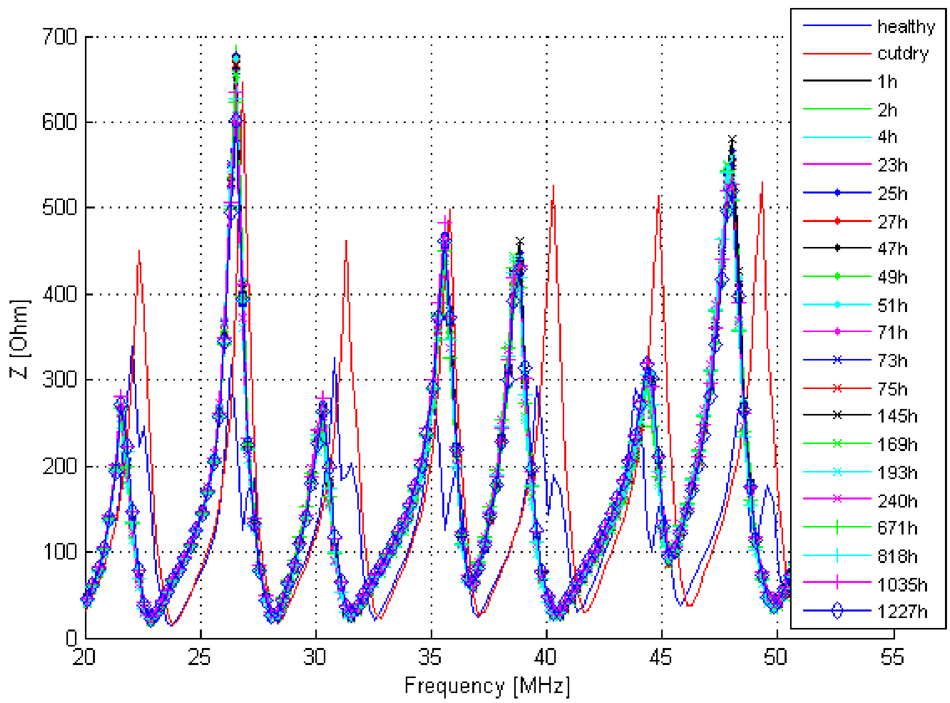


Fig. APII.0.10. AXMK cable (L1-L3), from 20 MHz to 50 MHz.

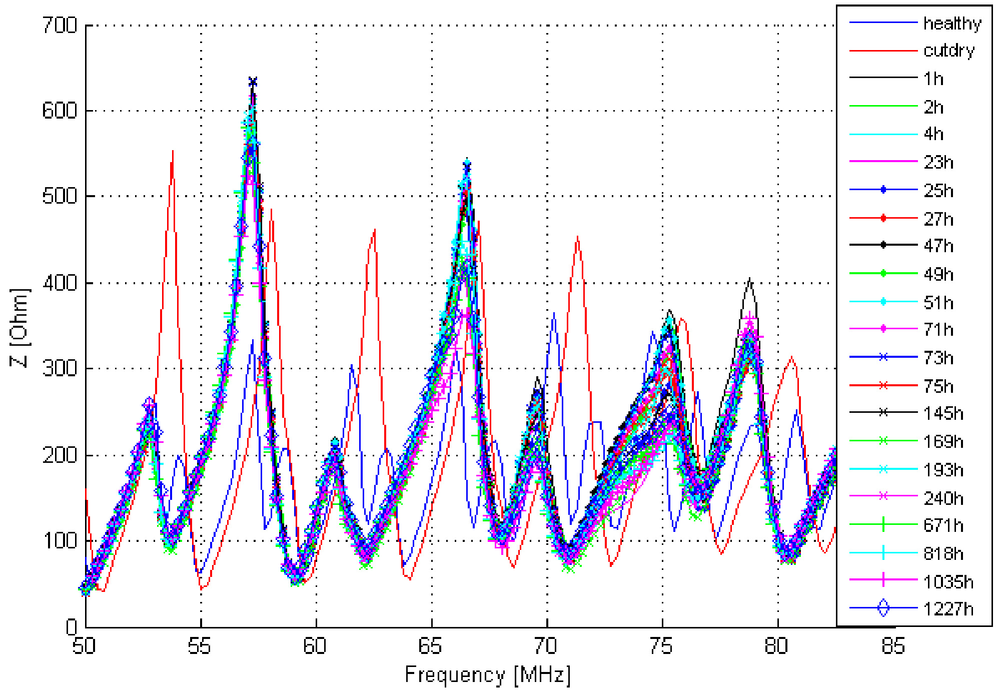


Fig. APII.0.11. AXMK cable (L1-L3), from 50 MHz to 80 MHz.

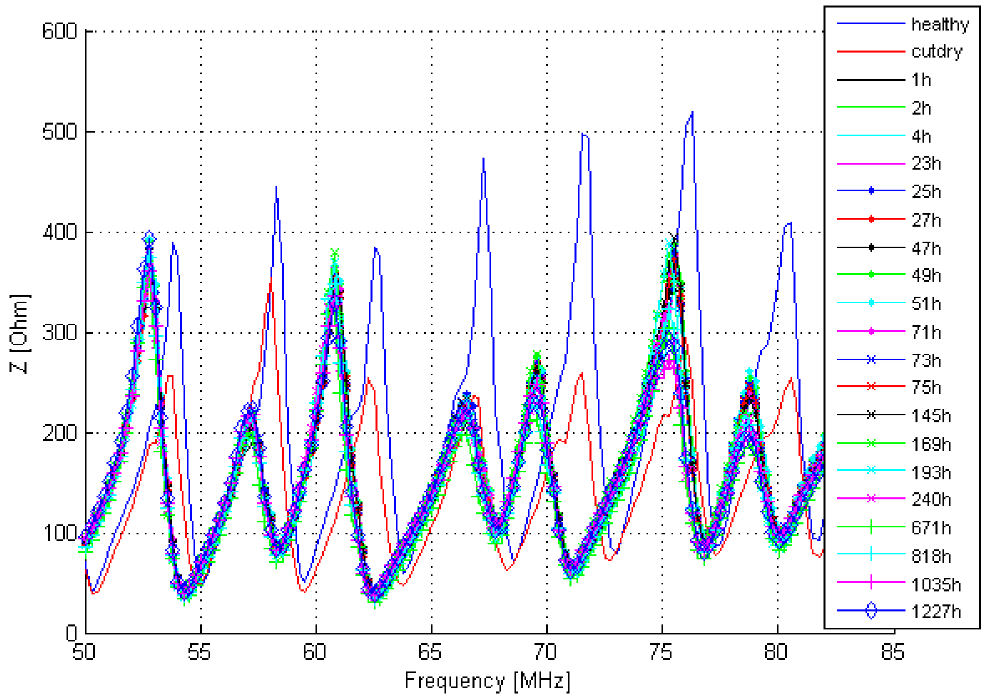


Fig. APII.0.12. AXMK cable (L1-PE) LTM, in the 50 MHz to 80 MHz range and from P25 to P0.