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Research Report Series

LC Channel Propagation Characteristics: A Survey of Measurements

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Research Report No. EE9
August 1993

Research Reports

This report is one of a continuing series of Research Reports published by the James Goldston Faculty of Engineering at the University of Central Queensland.

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DLC CHANNEL PROPAGATION CHARACTERISTICS :

A SURVEY OF MEASUREMENTS

BY

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RESEARCH REPORT No. EE 9

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF CENTRAL QUEENSLAND

26th August 1993

ABSTRACT

Knowledge of the power distribution network's propagation characteristics at communication frequencies is essential for optimum DLC system design. The available literature is reviewed to identify the propagation characteristics of the typical DLC channel. Although measurements represent a relative small sample there is clearly no typical channel. Measurements do tend to suggest channel classification using a limited set of typical channel types.

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1. INTRODUCTION

Although primarily designed for electric power reticulation, the Distribution Network (DN) can also be used as a communication system bearer. Many Distribution Line Carrier (DLC) Systems have appeared over the last 20 years, yet their performance has been far from acceptable as the sole communication medium in a Distribution Automation System. Meanwhile research and development continues to improve data transmission reliability as well as the data rate [1,2,3]. One reason for the slow progress is the poor propagation and noise characteristics of the typical DLC channel, which is defined as the connection between a typical DLC transmitter and receiver. This connection consists of the DLC terminal coupling-units and the multi-conductor, highly non-uniform, transmission line system that comprises the DN path. Imperfect knowledge of the channel's characteristics has impeded the optimum design of DLC data communication systems.

A number of researchers have conducted field measurements to determine typical DLC channel propagation characteristics. This report reviews the relevant literature in an attempt to identify the propagation characteristics of typical DLC channels. Specifically answers are sought to the following questions:

1. What DLC channel propagation characteristics have been measured, and how?
2. What do the reported measurements reveal about the typical DLC channel's propagation characteristics?

Another important DLC channel characteristic, noise, is considered in a separate report [4].

Most of the DLC literature originates in Europe and North America. European and North American DN structures are significantly different. In North American, typically a large number of relatively small, single-phase Distribution Transformers (DT) are connected across three-phase MV feeders at various points. Each DT secondary feeds only a small number of customers. In Europe, fewer, but larger three-phase DT's are employed, feeding large LV networks.

No references on DLC channel characteristics for Australian DN's could be located.

This report is restricted to DN's. The other two sections of the power reticulation network, the Transmission and Customer Networks, are not considered.

2. DISCUSSION ON MEASUREMENT TECHNIQUES

A number of DLC channel propagation characteristics have been measured by field experiments. Attenuation measurements are by far the most commonly reported. DN input impedance also receives considerable attention. Brief references to channel linearity tests [5], and group delay measurements [6], are also found.

It is not always possible to determine precisely what was measured because some reports do not give sufficient instrumentation detail and fail to clearly define the measured quantity. For example, although attenuation should be expressed as a power ratio between the point of injection and the point of reception one might suspect from some reports that a voltage ratio or voltage ratio squared was used. Coupling details are also essential for meaningful measurements. Typical DN transmission lines are multi-conductor structures which including the earth as part of their transmission path. The general characteristics should therefore be expressed in matrix quantities. Reported measurements however, are typically scalar quantities whose relationship to the general matrix depends on coupling details.

2.1 Coupling Methods

Coupling is the mechanism by which DLC signals are injected onto the power network. Parallel and series coupling are the two broad classes of techniques used. For parallel coupling signal voltages are connected between conductors or between conductors and earth using capacitors or DT's as the coupling element [7]. Series coupling injects signal currents into the DN conductors using coupling devices such as current transformers [7].

2.2 Attenuation Measurement Techniques

The basic approach of Attenuation Measurement is to couple a transmitter at one end of the DN path to be measured, and a receiver at the other end. Attenuation is calculated at a number of discrete frequencies using measured transmitted and received currents and voltages [8]. In order to isolate the DN path's attenuation characteristics the coupling-units' insertion losses must first be determined and subtracted from the overall attenuation figures. This is not always straight forward as the stochastic DN coupling-point impedance has a significant influence on the coupling-unit insertion loss [31]. It is therefore reasonable to assume, unless otherwise stated, that reported attenuation measurements include coupling-unit insertion loss.

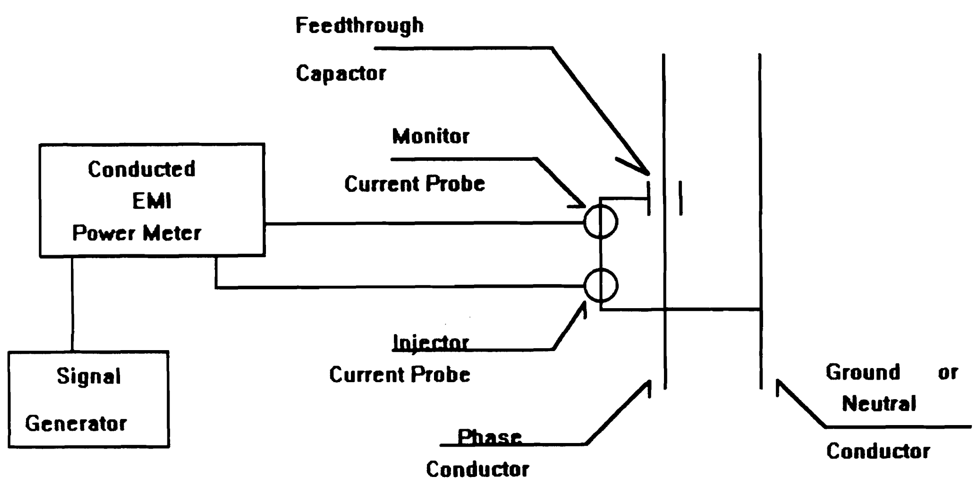
Rather than transmitting discrete frequencies some techniques inject a wideband signal with a flat spectrum and use a spectrum analyser at the receiver [9, 12]. Burr et.al. [9,19] used a sweep-frequency generator at the transmitter. Information on the instrumentation used in their experiment is sketchy. They did not appear to measure attenuation but rather the voltage or voltage square ratio as no mention is made of current or impedance. Wideband signalling could be an attractive technique. The difficulties of this method lies in the ability to measure the power ratios and the design of a coupling network for the wideband signal.

2.3 Impedance Measurement Techniques

Five different power line impedance measurement techniques have been found in the literature. They are summarised in Table 2.1 and discussed in the following sub-sections.

2.3.1 Two-Current-Probe Method.

Nicholson and Malack [10] measured impedances in LV networks in the frequency range 20kHz to 30MHz using a signal generator and a conducted electromagnetic interference power meter which employs the two-current-probe method [32]. Kwasniok et.al. [33] modified the technique to measure powerline impedances in the frequency range 500kHz to 500MHz using a network analyser in place of the power meter. Figure 2.1 shows the instrumentation used by Nicholson and Malack.



Impedance Measurement Instrumentation

Used by Nicholson and Malack [10]

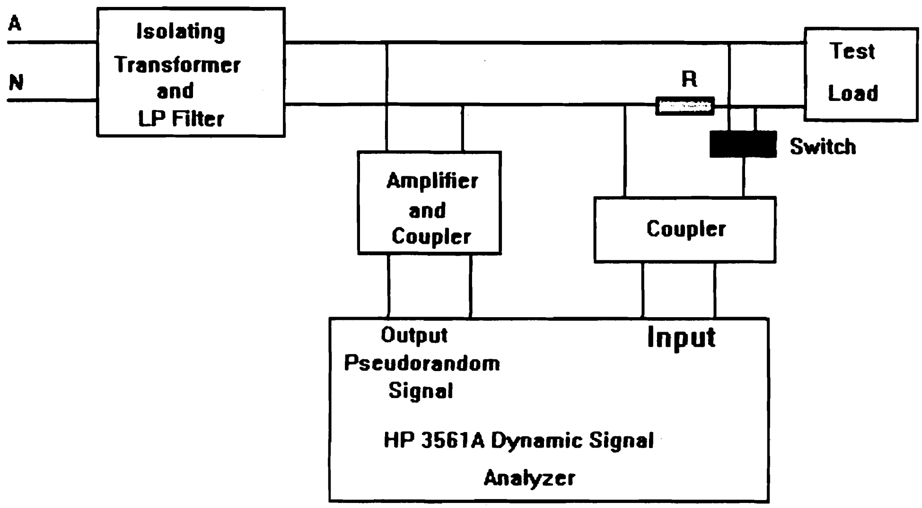
FIGURE 2.1

2.3.2 Voltage-Current Ratio Method

Vines et. al. [11], measured the current and voltage at the output of a signal generator connected to a filter whose output connected across two power conductors. As these measurements give an impedance that includes filter components, corrections were made for the filter impedance to give the desired measurements. Instrumentation details are given in [34].

2.3.3 Wide Band Signal Method

A novel method was used by Burr et. al. [9], to measure the impedance of customer loads up to 400kHz. They applied a wideband voltage signal to the load and measured the resulting current spectrum, the ratio of the two spectra gave the load admittance. The Electrical Engineering Department at the University of Central Queensland employed a similar method using a single channel dynamic signal analyser (HP 3861A).



Impedance Measurement Instrumentation Used at the University of Central Queensland [12]

FIGURE 2.2

The validity of the method was established, but the method's accuracy depended on the ability to isolate DN noise, which could prove difficult at times [12]. The instrumentation details are shown in Figure 2.2.

2.3.4 Oscillatory Transient Method

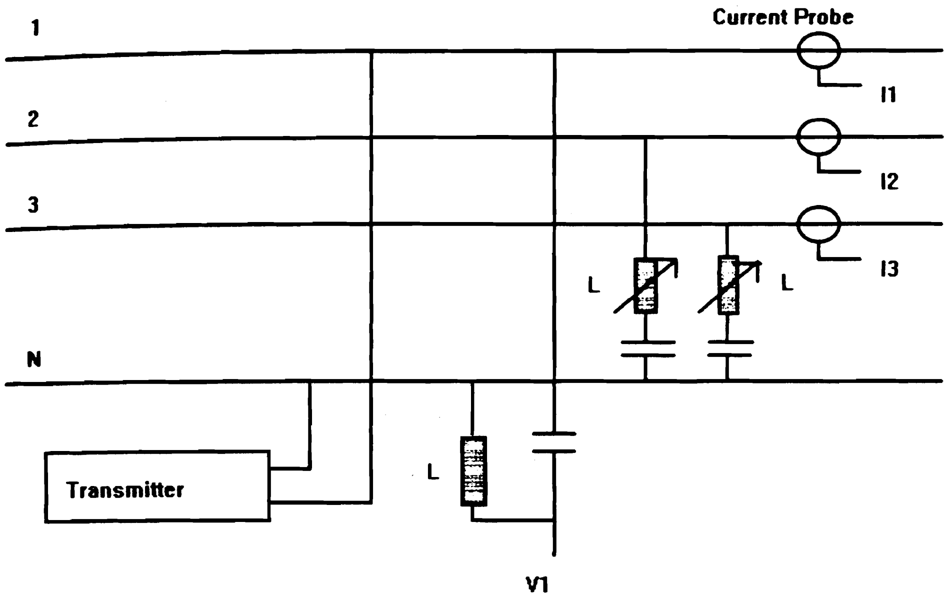
Forti and Millanta [35] described a method of determining the impedance of the power system at building power outlets. Known capacitors were switched between a phase conductor and neutral while observing the phase-to-ground and neutral-to-ground transient voltages. These capacitors were selected to produce an under damped transient. The values of the network model's inductance and resistance were calculated using the properties of the transient's oscillation and its damping ratio by solving the network transient equation of the R-L-C circuit.

The Oscillatory Transient Method is limited to low frequencies where line propagation phenomena can be neglected and the validity of the R-L power system model can be assumed. The authors suggested that the method might be used at frequencies below 50kHz, although in their experiments they only made measurements to 20kHz. It appears that the useable frequency limit would depend very much on the nature of the power network being measured and the accuracy required..

2.3.5 N-Terminal Network Y-Parameter Method

Rustay et.al. [13], measured elements of the driving-point admittance matrix $\mathbf{Y_D}$ at points on MV feeders using the classical method for determining n-terminal network Y-parameters. Applying a known voltage to each conductor in turn, with the other conductors held at near zero volts using tuned circuits, they measured conductor currents with current transformers. The ratios of the currents to the voltage gave the elements of the particular column of $\mathbf{Y_D}$. Figure 2.3 shows the general arrangement of their instrumentation.

Because of the MV network's high voltages this measurement technique could prove slow and expensive to perform.



Instrumentation Used by Rustay et.al. to Measure the Elements of the First Column of the Driving-Point Admittance Matrix

FIGURE 2.3

	MEASUREMENT[1] METHOD	REFERENCES	FREQUENCY [2] RANGE USED
1	Two-Current-Probe	[32], [10]	20kHz to 30MHz
		[33]	500kHz to 500MHz
2	Voltage-Current Ratio	[11], [34]	5kHz to 50kHz
3	Wide Band Signal	[9], [12]	2kHz to 400kHz
4	Oscillatory Transient	[35]	DC to 20kHz
5	N-Terminal Y-Parameter	[13]	5kHz to 50kHz

Summary of Power Line Impedance Measurement Techniques

TABLE 2.1

[1]The terms used here are not necessarily in common use.
[2]This frequency range does not necessilarly define the limiting range of the method.

3 REPORTED FINDINGS ON ATTENUATION MEASUREMENTS

This section surveys the findings of a critical study of published DN attenuation measurement projects. The European and North American DN's are treated separately because of their structural differences.

3.1 European MV Networks

In 1981, Realp et. al. [14], reported attenuation measurements made on four MV networks in Spain. It appears that parallel capacitive coupling, between an unspecified number of DN conductors and earth, was used. The coupling reactive elements were tuned to resonate with the imaginary part of the DN's input impedance, at each measurement frequency in a partial attempt to achieve impedance matching.

The first was an 11 kV cable network in Barcelona. Measurements were made between two points separated by 7.7km with 24 DT's connected along the length. Tests conducted in the frequency band 40 to 500kHz showed attenuation ranging from 22 to 50dB. Attenuation tended to increase with frequency but not monotonically. The attenuation vs. frequency characteristic contained peaks and troughs. Network topology changes such as isolating the feeder from the sub-station bus-bar and connecting shunt capacitors changed the attenuation by up to 7dB. For a given topology however attenuation remained constant with time. They confirmed earlier findings by others [15,26], that DT's connected across MV feeders had negligible effect on propagation over a similar frequency range. Figure 3.1 shows a plot of the reported measurements.

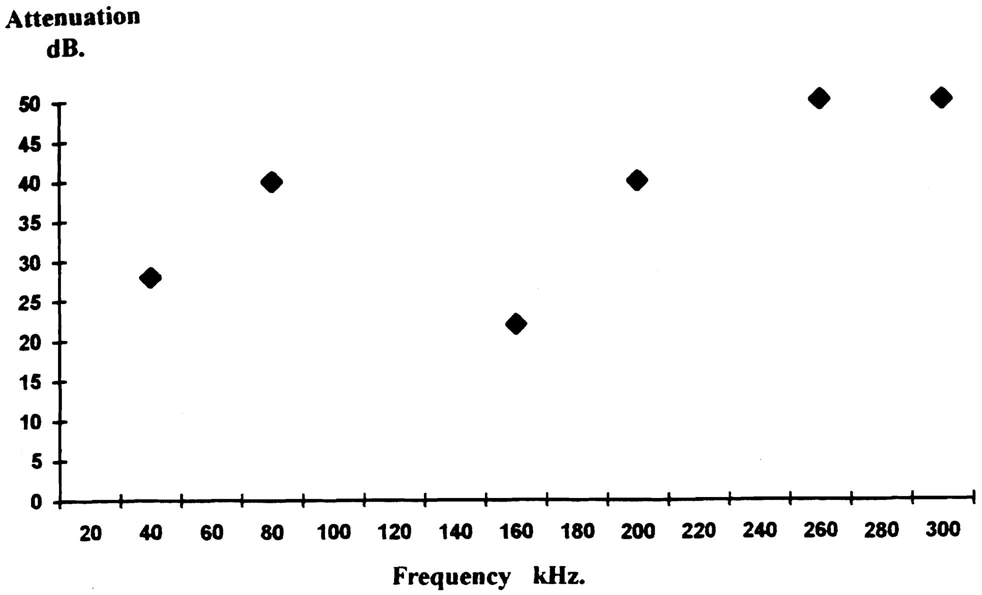


FIGURE 3.1

The second test was on a 2.6km cable feeder with 7 DT's in Madrid. It was tested in the frequency band 40 to 320kHz. Attenuation was found to be between 27 and 43dB. A 1.7km duplex feeder without DT's was the object of the third reported test. Attenuation ranged from as low as 14dB at 260kHz to 38dB at an unspecified frequency. As the bus-bar configuration at both ends of the feeder were changed the attenuation at 260kHz varied from 11 to 18dB confirming again the dependence of path attenuation on network topology.

The fourth test measured attenuation on a 1.7km feeder, containing 0.7km. of open-wire construction. Attenuation reached more than 70dB at certain frequencies. The cause was attributed to the cable-open-wire discontinuity. No details of the notch frequencies or widths were given. The lowest attenuation was 26dB.

DeMichels et. al. [7], in 1985 reported measuring the attenuation of a typical Italian MV cable network at three discrete frequencies between 35 and 80kHz using parallel capacitive coupling between one conductor and earth. Attenuation ranged between 14 and 21dB. Tests were also conducted using series coupling in the 10 to 60kHz range. Quantitative measurement details were not supplied. It was reported that the tests demonstrated the possibility of obtaining adequate signal-to-noise ratio values for DLC systems to operate satisfactorily via DN paths a few kilometres long. For both tests attenuation did not vary significantly with frequency or time.

Austfeld [16], 1983, gives examples of the attenuation characteristics of typical Swiss MV networks. A current transformer connected the receiver to an MV/HV substation bus. The transmitter injected a signal at the LV network side of a DT, but coupling details were not given. In the first example the attenuation of a 5.5km cable feeder varied from 11 to 42dB, in the frequency range 2 to 20kHz. The second example were characteristics of a 7.7km feeder, containing 5.6km of open-wire construction, which had a 60dB resonant notch at 6.5kHz and had generally higher attenuation. Attenuation characteristics tended to exhibit peaks and troughs and attenuation increased with frequency.

Hoeffelmann et. al. [17], 1987, gives the attenuation of a 10km MV cable feeder at a number of discrete frequencies between 4 and 30kHz. Attenuation ranged from 6 to 21 dB, and the characteristic contained the typical peaks and troughs. Coupling details were not given.

The familiar frequency selective attenuation characteristics were also reported by McMillan et. al. [18], 1987, when measuring a United Kingdom (UK) MV cable network. They attributed this characteristic predominantly to the variation in transmitter coupling-unit insertion loss with frequency, due to DN input impedance changes. No substantial argument was made to support this conclusion. Series coupling was used to inject a broad band signal into an unspecified number of DN conductors. The receivers used series, and parallel capacitive coupling.

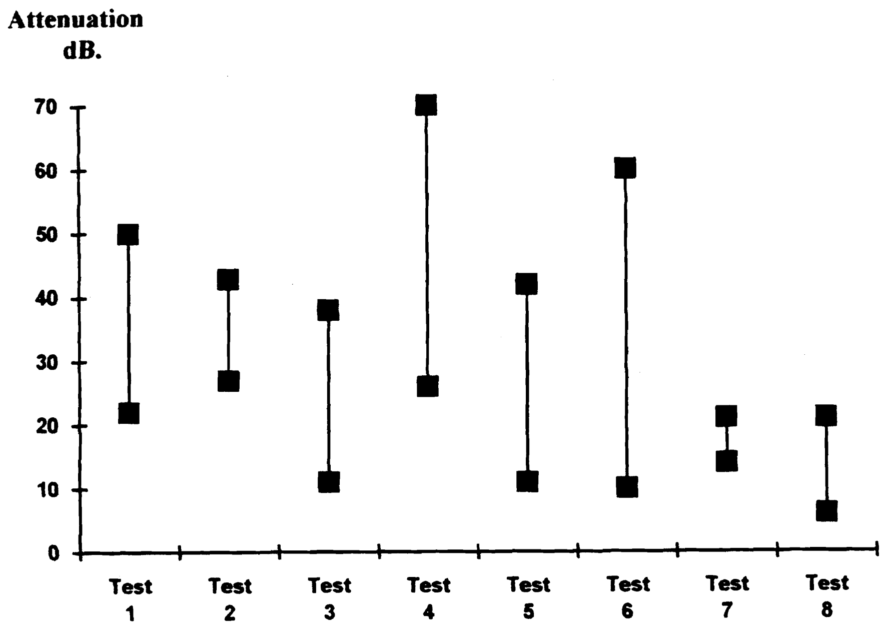
European MV network attenuation measurements are summarised in Table 3.1 and Figures 3.2 and 3.3 where the test number refers to the table entry.

	YEAR; REFERENCE; LOCATION	NETWORK TYPE	LENGTH[3] km.	COUPLING	FREQ. RANGE kHz	MAX./MIN. ATTEN. dB	COMMENTS
1	1981;[14] Barcelona	11Kv cable	7.7	capacitive	40 to 500	22 to 50	24 DT's, min. at 160kHz
2	1981;[14] Madrid	15kV cable	2.6	capacitive	40 to 320	27 to 43	7 DT's
3	1981;[14] Madrid	15kV cable	1.7	capacitive	40 to 320	14 to 38	no DT's,min. at 260kHz
4	1981;[14] Madrid	15kV mixed	1.7	capacitive	40 to 320	26 to > 70	DT details NG[4]
5	1983;[16] Switzerland	10kV cable	5.5	rec.-series trans.-NG	2 to 20	11 to 42	path was via DT
6	1983;[16] Switzerland	10kV mixed	7.7	rec.-series trans.-NG	2 to 20	10 to 60	path was via DT
7	1985;[7] Italy	20kV cable	NG	capacitive one cond. to earth	35 to 80	14 to 21	
8	1987;[17] NG	MV cable	10	NG	4 to 30	6 to 21	

Summary of European MV network attenuation measurements

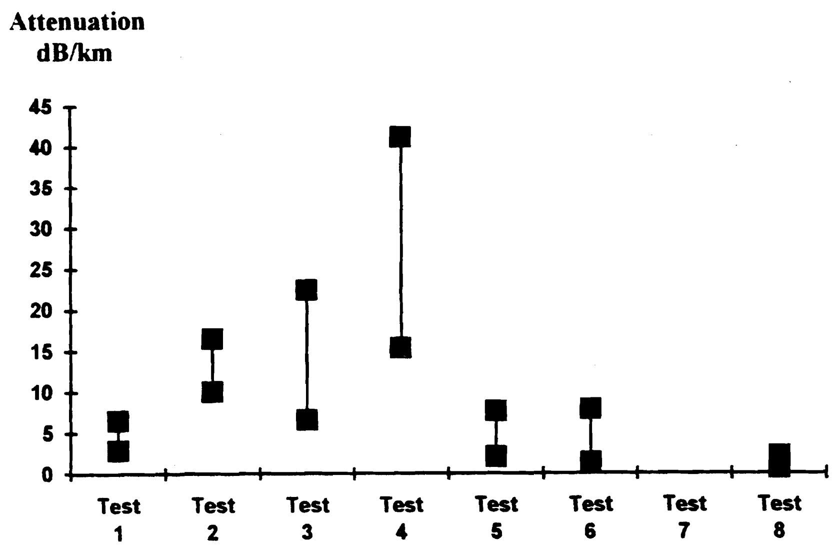
TABLE 3.1

[3]Length is the distance between test points.
[4]NG indicates that information is not given.



European MV network measurements, range of attenuation.

FIGURE 3.2



European MV network measurements, range of attenuation per kilometre.

FIGURE 3.3

3.2 European LV Networks

This section discusses attenuation measurements of the LV network in Europe. LV networks have path lengths typically an order-of-magnitude shorter than MV networks. However the number of impedance discontinuity's per unit length is comparably greater.

In 1982, Burr et. al. [19] studied propagation in typical UK LV cable networks using measurements and computer simulation on a 300 metre network path. Propagation characteristic measurements in the frequency range 20 to 500kHz, using wide band signal injection techniques, were derived using a spectrum analyser. Unfortunately the terms propagation and attenuation were used without a clear definition and it appears that the calculations were made using either a voltage or voltage square ratio. Measurements were made at 5pm and 8.30pm on the same day. Signal "attenuation" was found to be greater than 30dB for the 5pm measurement. Typical peaks and troughs in the attenuation characteristic as the frequency varied was observed. "Attenuation" at 8.20pm was generally 10dB higher, and at some frequencies, 30dB higher than the corresponding values at 5pm. The characteristic peaks and troughs had also changed their form and position at the two different times. The spectrum analyser displays also identified a "noise floor". From these displays the most appropriate communication system operating frequency, based on signal-to-noise-ratio (SNR), were observed to be between 200 to 430kHz. This frequency band, however did not appear to remain stationary.

Similar measurements on another UK LV cable network, in the frequency band 20 to 200kHz, were reported in Burr et. al.'s 1987 paper [9]. The experiment confirmed the non-stationary nature of a given path's attenuation characteristic. It showed, from measurements and simulation, that the cause was predominantly customer loads. Particular loads consisting of potential resonating components could have a dramatic effect when connected to the network. The most influential loads were found to be street lighting systems which increased signal attenuation at some frequencies by up to 50dB.

Other measurements in Belgium and the UK [6,18,20] also confirmed the frequency selective and non-stationary nature of LV network attenuation characteristics. After studying the attenuation characteristics of a number of different cable sections in a variety of Swedish LV networks, Hagmann [21], 1989, concluded that no systematic general relationship existed between LV network path attenuation and frequency. Measured attenuation ranged from a few dB to over 50dB. However all characteristics contained peaks and troughs both of which varied slowly with time. ASEA Brown Boveri (ABB), field tests in Switzerland showed that LV measurements averaged approximately 100dB/km while MV networks averaged less than 10dB/km, [22].

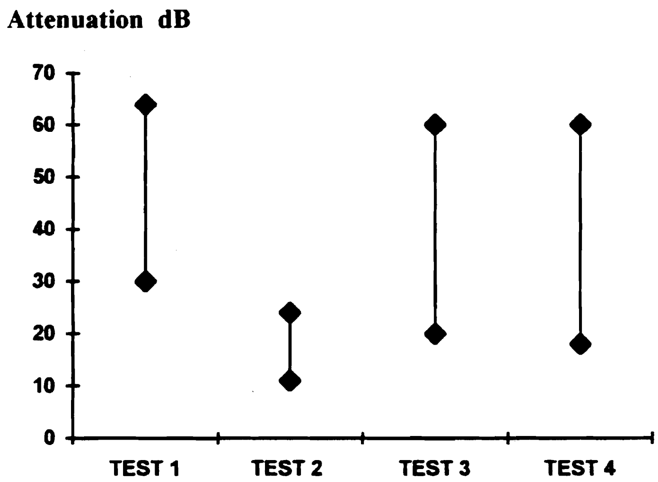
European LV attenuation measurements are summarised in Table 3.2 and Figures 3.4 and 3.5 were test numbers refer to the table entry.

	YEAR; REFERENCE LOCATION	**NETWORK TYPE**	**LENGTH m.**	**COUPLING**	**FREQUENCY RANGE kHz**	**MAX./MIN. ATTEN. dB**
1	1982;[19] UK	415V cable	300	NG[5]	20 to 500	30 to 64
2	1982;[20] UK	415V cable	NG	NG	1 to 100	11 to 24
3	1987;[9] UK	415V cable	NG	NG	20 to 200	20 to 60
4	1990;[6] Belgium	LV cable	350	NG	10 to 100	18 to 60

Summary of European LV network attenuation measurements

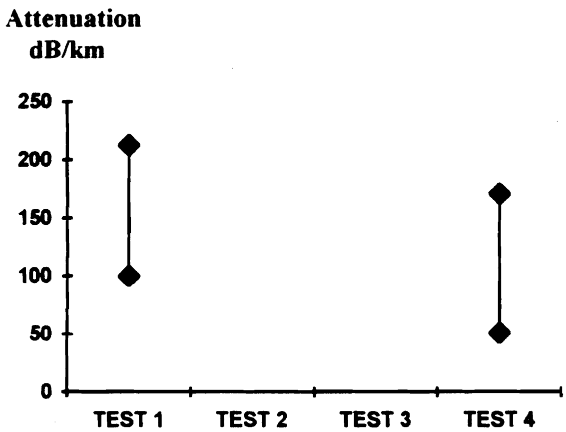
TABLE 3.2

[5] NG indicates that information was not given.



European LV networks, range of attenuation measurements

FIGURE 3.4



European LV networks, range of attenuation per kilometre

FIGURE 3.5

3.3 North American Measurements

In the 1970's a number of companies including Rockwell International and General Electric began DLC systems experimentation and conducted field measurements [23,24]. The results confirmed that attenuation of signal paths via DT's, was significant at frequencies as low as 15kHz, and prohibitive at frequencies above 50kHz. The typical attenuation characteristic included a 18dB/octave roll-off, where the break point frequency varied between feeders. Measurements showed that 3 to 10kHz was the appropriate frequency band for DLC systems [23]. By the 1980's the frequency range 5 to 15kHz was established as the preferred DLC band in the US [25].

From the experiments it was observed that feeders employing exclusively MV cables measured much lower attenuation than open-wire feeders. This finding may appear confusing given that cable can have attenuation values an order of magnitude higher than open-wire. One theory that has been advanced is that network impedance discontinuities are the most significant cause of DN attenuation [36].

It was further observed that feeders with a high, impedance discontinuity density did not contain significant standing waves, while low discontinuity density feeders did [24]. This can be explained from transmission line theory which predicts that for standing waves to exist electrically long, relatively uniform lines are required.

Ontario Hydro Research in the early 1980's conducted attenuation measurements on an 11km semi-rural feeder in Canada at five discrete frequencies between 2 and 20kHz [8]. They used parallel capacitive coupling between one conductor and earth. Results were presented as statistical currents and voltages and it is difficult to accurately determine the attenuation. However it is clear that attenuation did vary with frequency, time and receiver position although the variations with time were generally not as dramatic as Burr et. al.'s

LV measurements [9]. Evidence of standing waves was found as well as significant coupling of signals between DN conductors.

Hemminger et.al. [27], 1987, conducted controlled experiments on a non-branched, unenergized, 6.3km, single-phase, open-wire, 23kV line. The line was part of a test facility owned by Carolina Power and Light Company. They found that attenuation was below 1dB/km for frequencies up to 50kHz, even when loaded by DT's with short-circuit or open-circuit secondaries. Standing waves on the line could produce weak signals at certain locations and frequencies. Their conclusion was that DT secondary loads had little effect on attenuation and that the main cause of attenuation on "real" MV lines was the signal branching at laterals. While their conclusion appeared to agree with European experimental results at higher frequencies, they opposed the conventual wisdom and were strongly criticised.

Rustay et.al. [13], 1979, conducted measurements for the purpose of verifying an RF communication DN channel computer model they developed at GEC for the US Department of Energy and the Jet Propulsion Laboratories. The elements of voltage transfer ratio matrices were measured in the frequency range 5 to 45kHz. Initial measurements on a 4km section of an open-wire feeder with no major branching showed that DT loading had little influence on MV propagation. At the higher frequencies standing waves appeared causing the low signal voltages along the feeder [13]. These observations were used by Hemminger et.al.'s to support their later findings [27]. Rustay et.al., in phase II of their project, extended verification measurements to a greater variety of situations and network size. These tests indicated that DT secondary loading could effect feeder voltage transfer ratios, particularly on feeders with a high number of DT's per unit length.

Suh et.al. [2], 1991, conducted experiments on an unenergised and unloaded three-phase symmetric and asymmetric lines at a test facility owned by Carolina Power and Light Company. Injecting signals at a frequency of 25kHz, they showed that standing waves could exist and that they could sometimes be difficult to predict for asymmetric lines using classical single-phase transmission line techniques. It was observed that standing wave voltage nulls and current peaks generally occurred at the same location and there was significant coupling between conductors. It was further observed that a three-phase symmetric line with each conductor having the same load and source connections, behaved as a bundled conductor.

Because of the lack of quantitative detail it is not possible to construct tables and graphs for the North American measurements.

4. IMPEDANCE MEASUREMENTS

Because the DN is a multi-conductor system the general network impedance must be represented by a matrix. It is therefore important to include instrumentation connection details when offering scalar quantities as impedance measurements. Most reported impedance measurements are from LV networks. This reflects the difficulties in making MV measurements.

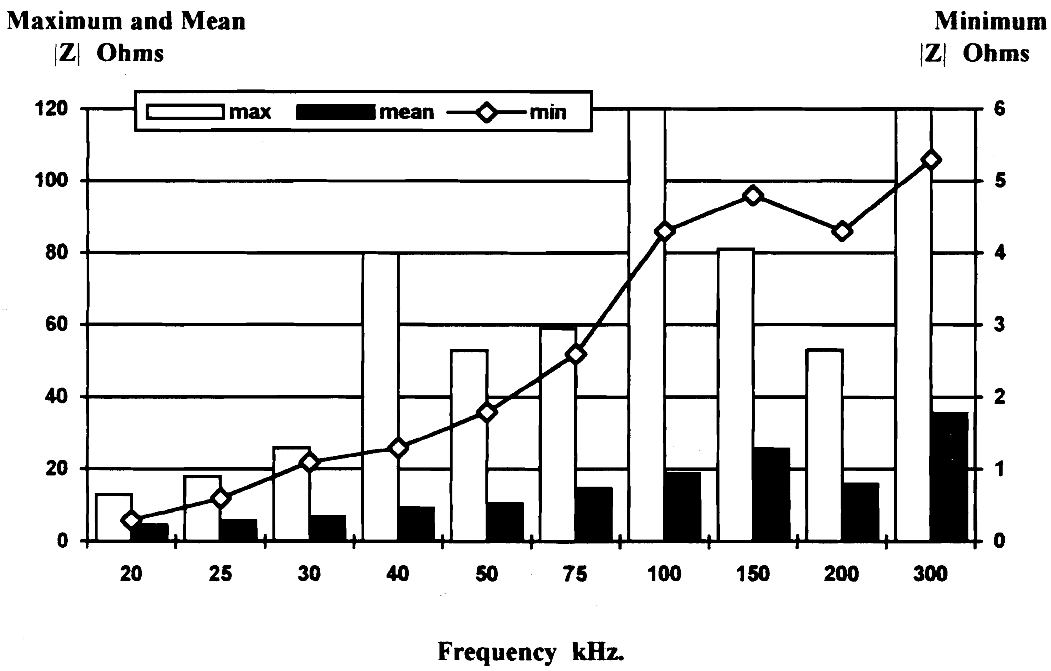
4.1 European MV Networks

No reported European MV network impedance measurements could be found in the literature. Realp et.al. [14], used return loss measurements to calculate the input impedance of coupling-units connected to MV cable networks in Spain. At each measurement frequency in the range 40kHz to 500kHz they adjusted the coupling-unit's reactive elements to produce a real impedance at the input. These impedances ranged from 10 to 70 Ohms. Little detail was given.

4.2 European LV Networks

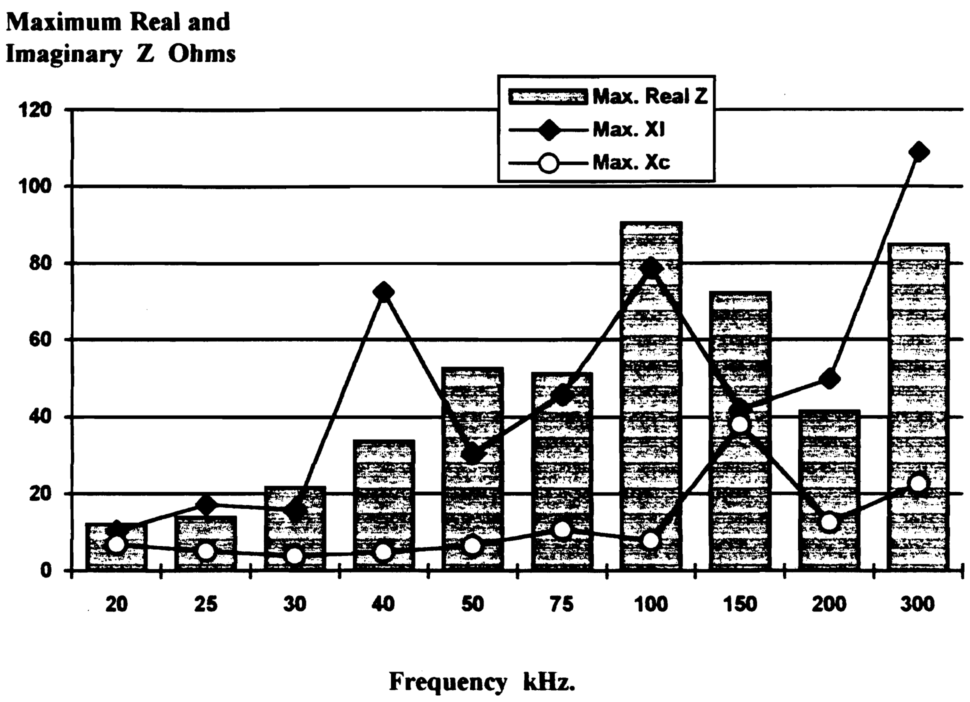
Malack and Engstrom [28] measured impedance at 86 Customers in 10 different European countries at 25 discrete frequencies in the band 20kHz to 30MHz. They made measurements between a phase conductor (arbitrarily chosen in the case of multi conductor circuits) and the safety ground wire. Measurements varied little between countries. Minimum real impedances were observed to range from near zero at the lower frequencies to 3.3 Ohms at 300kHz. Figure 4.1 summarises the impedance magnitude measurements in the band 20kHz to 300kHz. Maximum real and imaginary impedances computed by Malack and Engstrom are plotted in Figure 4.2.

Impedance measurements of UK LV network loads at frequencies up to 400kHz were reported by Burr et. al. [9,19]. Impedance changed non-deterministically as customer loads were turned on and off. At very light loads the impedance was capacitive, which was attributed to customer's wiring. Resonance was commonly observed with admittance peaks as high as 1.5S (0.67Ω) for customer's loads, and up to 5S (0.2Ω) for street lighting. Resonant frequencies were typically above 30kHz with Q-factors not exceeding 8. It was observed that the load's 50Hz characteristics bore little resemblance to impedance characteristics at higher frequencies.



Maximum, mean and minimum European LV impedance magnitude measurements [28]

FIGURE 4.1



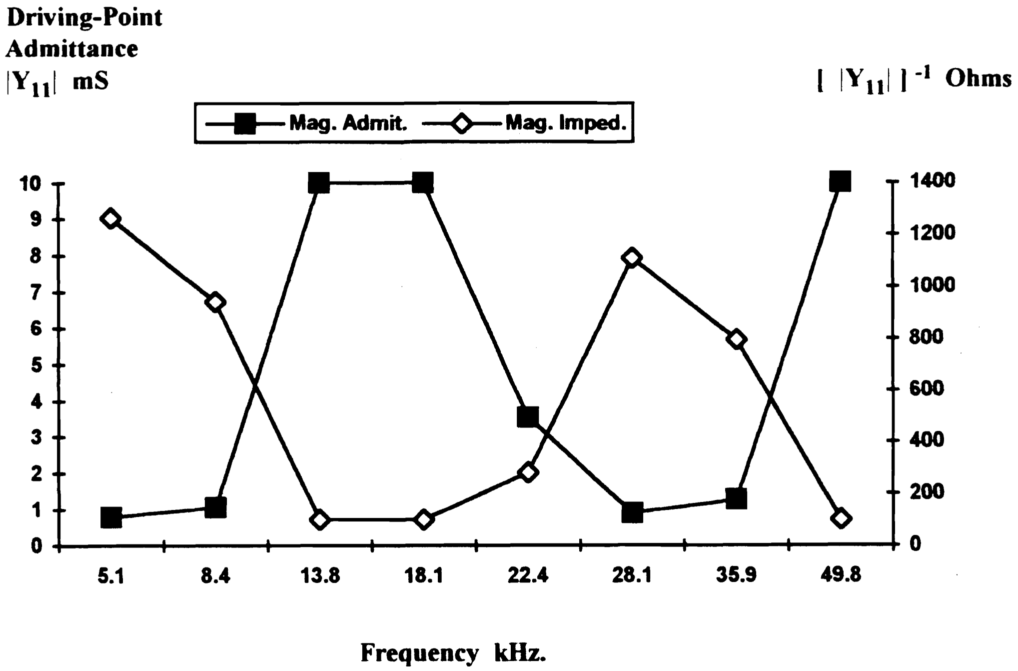
European LV network maximum real and imaginary impedance measurements [28]

FIGURE 4.2

4.3 North American MV Networks

GE made the only published driving-point admittance matrix measurements on MV networks in their attempt to verify a computer package for estimating DLC signal propagation [13]. Measurements were made on a relatively uniform, 4km branch of a 13.8 kV feeder at a number of discrete frequencies between 5 and 50kHz. The end of the feeder was open-circuit. The magnitudes of all admittance measurements were below 25 mS, (40 Ω), with some as low as 0.18 mS, (5560 Ω). The diagonal matrix elements displayed variations with frequency typical of standing waves. (see Figure 4.3). Further measurements also demonstrated characteristic standing wave behaviour and the effects of a matched termination.

In a second test the admittance of one phase at a substation was monitored over a period of three days at four discrete frequencies between 5 and 40kHz. The experiment revealed a diurnal variation at all frequencies while smaller variations occurred at higher frequencies. At 5.13 kHz the admittance magnitude ranged from 10 mS (100Ω) to 36 mS (27.8Ω) with a mean of 20 mS (50Ω) it was predominantly resistive. Because of calibration problems this range could in fact be twice as large. Admittance magnitudes ranged from 18 mS (55.6Ω) to 31 mS (32.3Ω), at 40 kHz , with a mean of 24 mS (41.7 Ω). It was typically capacitive.



Diagonal element, $|Y_{11}|$, of measured driving-point impedance matrix [13]

FIGURE 4.3

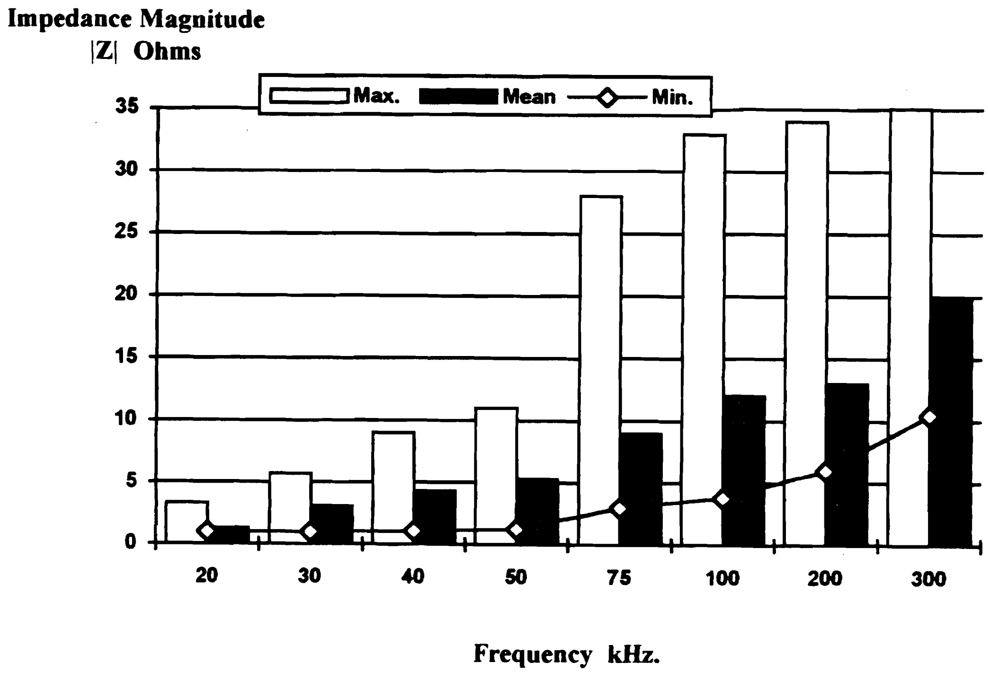
The third network measured was a 1.6 km underground MV feeder with single-phase underground cable branches. The driving-point admittance matrix diagonal element magnitudes, measured at discrete frequencies between 5 and 25 kHz, ranged from 1S (1Ω) to 33 mS (33Ω). The effects of standing waves were evident. Off-diagonal matrix elements were 30dB smaller reflecting the effect of shielding between separate phase cables.

A fourth tests made on a mixed feeder consisting of 0.65km of open-wire and 0.5km underground cable gave magnitudes for the driving-point admittance matrix diagonal elements ranging from 8 mS (125Ω) to 333 mS (3Ω). They were generally inductive, particularly at higher frequencies. Unlike the entirely underground feeder, off-diagonal elements were significant, ranging from 2 mS (500Ω) to 100 mS (10Ω). This was attributed to inter-phase coupling in the short open-wire section.

4.4 North American LV Networks

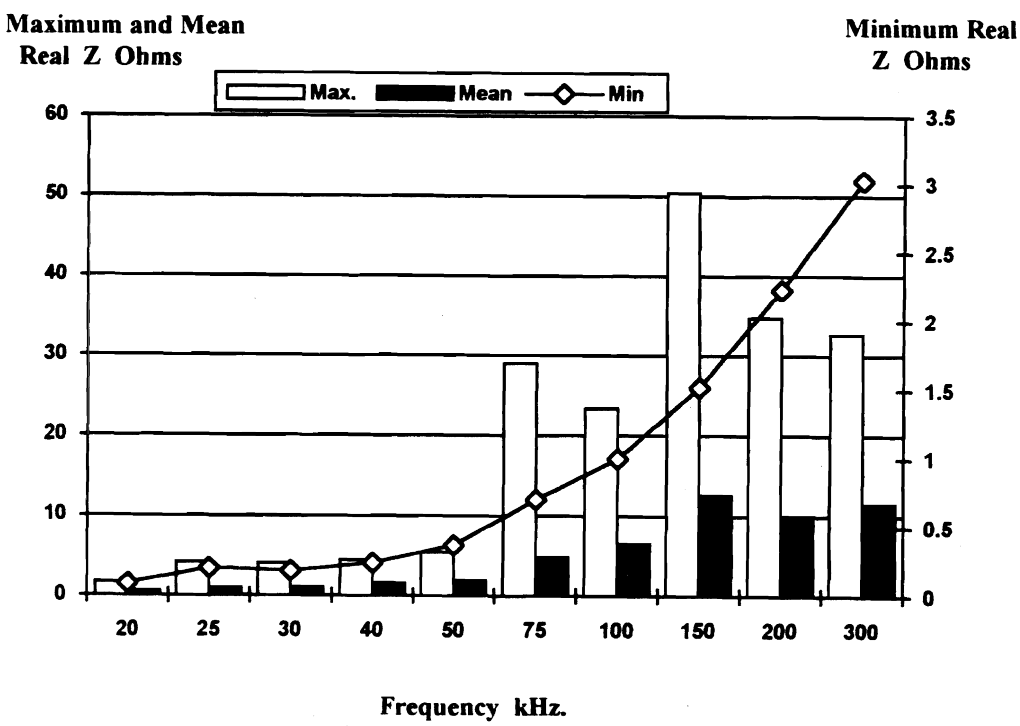
Nicholson and Malack [10] measured impedances at 36 US customers at 25 discrete frequencies between 20kHz and 30MHz. They made measurements at both the phase and neutral lines with respect to the safety ground on single-phase three-wire lines, and between each phase and neutral on three-phase, four-wire lines. The measurements in the frequency band 20kHz to 300kHz are summarised in Figures 4.4 to 4.7. Figure 4.8 compares the mean of impedance magnitude measurements with those made by Nicholson and Malack [28] on European LV networks.

Vines et.al. [11] measured the impedance of US LV circuits in the frequency band 5 to 50kHz. They measured both the 240V and 120V circuits of six urban residences with and without resistive loads. It was observed that the measured impedance tended to increase with frequency and was lower when resistive loads where connected. Connection of resistive loads caused the greatest impedances changes at the lower frequencies. Observed resonances were generally above 40kHz. At higher frequencies the loads remote from the measuring point appeared to have little effect on the network impedance measured at the driving point. The measurement results substantially agreed with those obtained by Nicholson and Malack.



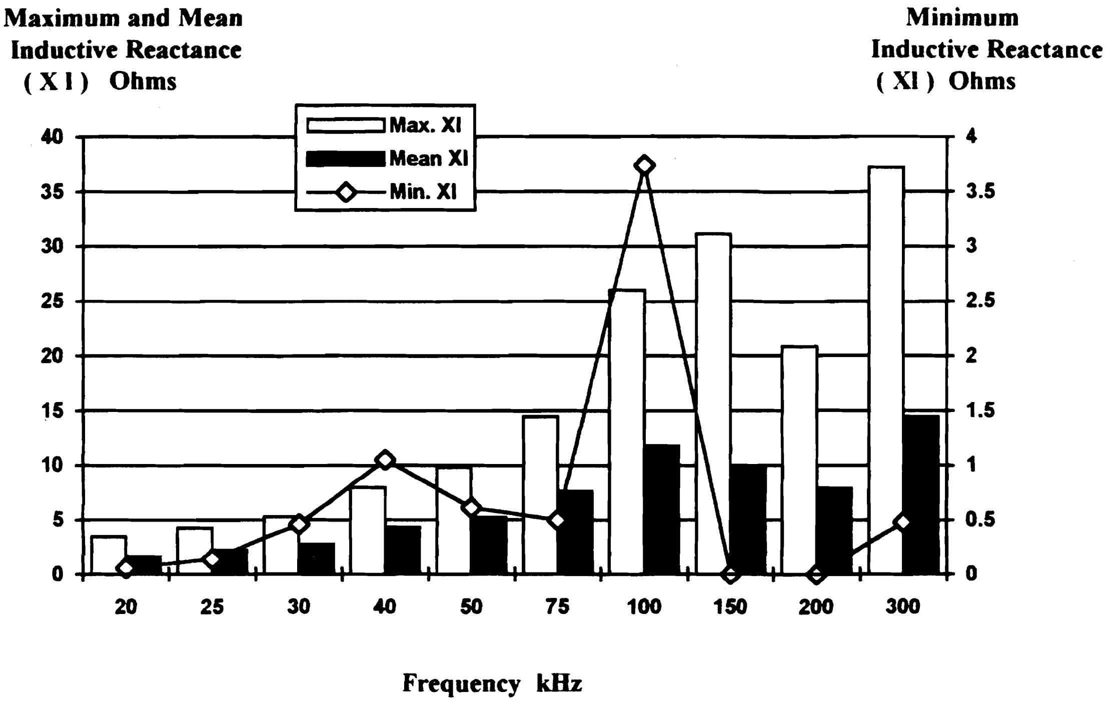
Maximum, mean and minimum North American LV impedance magnitude measurements [10]

FIGURE 4.4



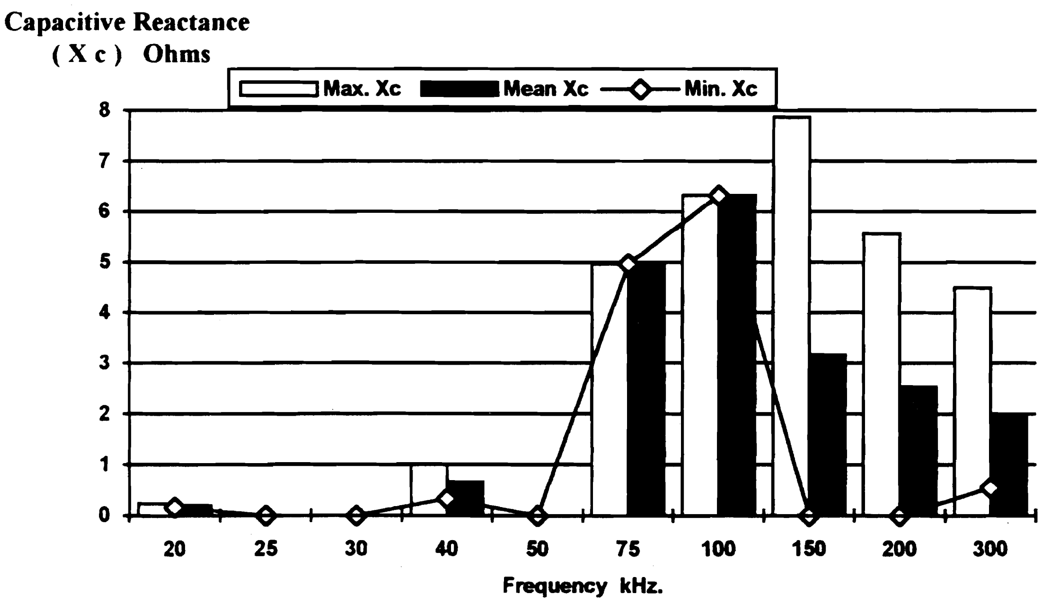
Maximum, mean and minimum North American LV network real impedance measurements [10]

FIGURE 4.5



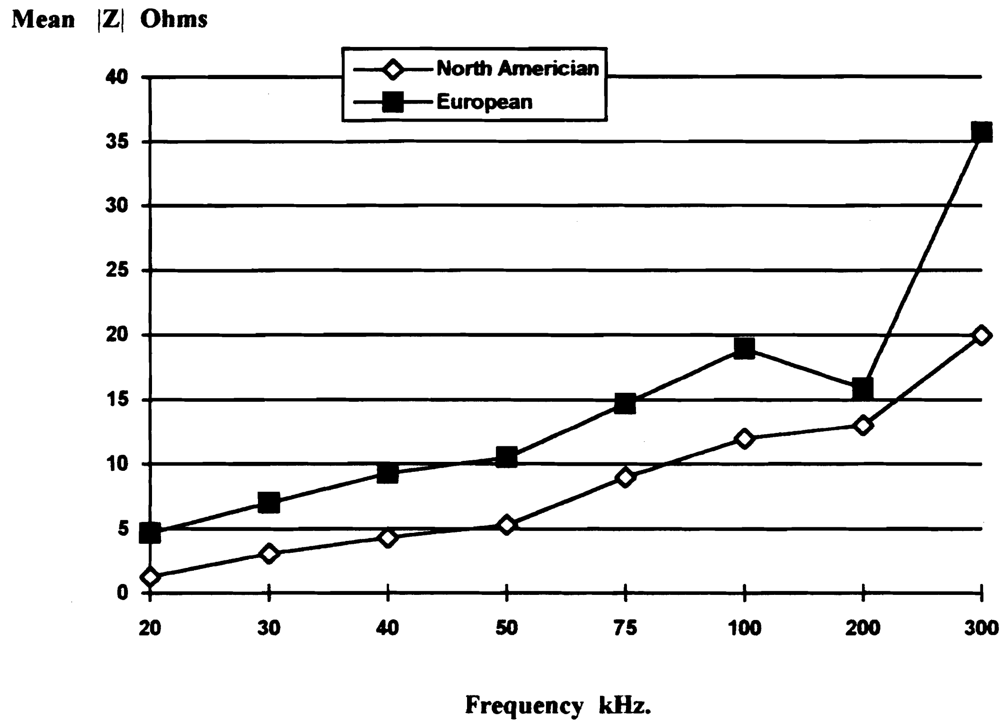
Maximum, mean and minimum North American LV network inductance measurements [10]

FIGURE 4.6



Maximum, mean and minimum North American LV network capacitive reactance measurements [10]

FIGURE 4.7



Comparison of mean North American and European LV network impedance magnitude measurements [10]

FIGURE 4.8

5. OTHER MEASUREMENTS

Is the typical DLC channel linear? Shekel [5], argued that although DT's display nonlinearities at power frequencies, their characteristics are essentially linear at the low signal levels used by DLC systems. Tests conducted by Bell Telephone Laboratories and American Science and Engineering, inc. confirmed this [5].

Radiated and conducted measurements, made over a three year period, on 100 feeders at 10 utilities across the USA, studied noise and observed DLC signals [25]. On only one occasion were DLC intermodulation signals observed and then the offending nonlinearity could not be located to confirm that it normally resided in the DN.

There was one reported group delay measurement in the literature [6]. A sample plot over the frequency range 10 to 95kHz showed group delay varying with frequency with a range of approximately 0.1 ms. A single channel metrology was used as described in [29].

6. DISCUSSION and CONCLUSIONS

The DLC channel consists of terminal coupling-units as well as the DN path. It is important that the individual characteristics of these basic elements and their interdependence be considered when studying DLC signal propagation. The coupling-units are part of the system design and their characteristics may be controlled within limits using appropriate strategies [31]. The DN path's characteristics are typically stochastic and beyond the designer's control. Both channel elements may interact with each other. Coupling-unit insertion loss will be influenced by the DN path's input impedance and since coupling-units appear as network loads they may change path characteristics [31]. Because instrumentation must include coupling-units of some form, interaction between elements may occur. This fact has been ignored in reported measurements. As the result, the characteristics of the basic channel elements were not identified.

While the number of reported measurement projects were small, some general observations can be made,

- All DLC channels tend to have high attenuation. The channel attenuation tends to increase with frequency and contain peaks and troughs. The pattern of peaks and troughs may be unique to a particular network topology, propagation path and time.

- The number and nature of impedance discontinuities, rather than path length, has a larger impact on path attenuation.

- Standing wave patterns of voltage and current signals exist on electrically long lines with few discontinuities. Standing wave patterns tend to be less distinct for lines with large numbers of discontinuities.

- Channel modelling using linear networks appears reasonable although supporting evidence is only available from US networks in the DLC frequency band below 15kHz.

- Most DLC channels exhibit slow varying nonstationary propagation characteristics, displaying large variance and frequency selective fading. However channel characteristics may be considered to be essentially constant during the transmission of a typical information unit.

- The DT has a significant effect on DN path propagation. For a DN path incorporating the DT the attenuation of signals passing through the DT increases with frequency. Above a frequency between 15 and 50kHz, the DT may acts as an isolator resulting in prohibitively high attenuation. DT also tends to isolate MV network paths from their LV networks causing stationary attenuation.

- LV network impedance is typically lower than that of the MV network. European type networks tend to have higher impedance than North American networks. Typically impedance varies with network topology, measuring point location, frequency and time. The impedance of the MV network tends to becomes more stationary at higher frequencies.

- Measurements clearly show that there is no typical DLC channel. They however tend to suggest channel classification by a limited set of typical channel types. The broadest classification would include the following types that tend to share common characteristics.

1. Channels whose paths contain DT's.
2. Channels whose paths are restricted to an MV network.
3. Channels whose paths are restricted to an LV network.

There are clearly sub-divisions within each classification that involves parameters such as operating frequency, line types, impedance discontinuity density, whether the DN has a North American or European topology, etc. This is discussed in more detail in [36].

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