POWER LINE COMMUNICATION

The power line communications channel is a notoriously bad channel that has been developed without regard for any communications considerations. However, it is so widely distributed that considerable cost savings can be achieved if use is made of its cable infrastructure.

Power line communications is a topic that has been studied for many years, although it has never been in the mainstream of communications research activities. During World War II, some radio amateurs experimented with power line communications, when their activities on the radio frequency spectrum were restricted. As early as June 1954, the American Institute of Electrical Engineers (AIEE) published a report entitled *Guide to Application and Treatment of Channels for Power Line Carrier,* which was updated in 1980 (1). In the time since, the results of several investigations have been published and a number of commercially available systems have been developed. Some of these results are reported in our bibliography, which is certainly not exhaustive but which can serve as an introduction to this area in communications.

Electrical power lines are usually classified into the high (>100 kV), medium (1 kV to 100 kV) and low (<1 kV) voltage networks, with respectively increasing communications difficulties. (Note that the aforementioned voltages represent rather loose bounds on the effective voltage values, measured between phases in a three-phase network.) Much of the past research has focused on low-voltage electrical power distribution networks, which are also geographically the widest spread and which usually have the most convenient access within various buildings and structures.

This article thus focuses primarily on communications systems for the hostile low-voltage network (i.e., the so-called distribution line communications [DLC] systems).

APPLICATIONS

Historically, the utility organizations have been an important driving force behind the development of power line communications. A primary motivation has been to achieve load management. This is usually achieved by selective switching off at times of peak demand, devices such as water heaters, which consume much energy at the demand side. Some countries employ a ripple control system for this purpose. A ripple control system is a unidirectional system with low data rates that typically operates in the frequency band below 3 kHz, and it has the disadvantage that it may require several megawatts for information transmission. However, more sophisticated bidirectional DLC systems are seen as the ultimate system for tariff switching, enabling a more leveled load of the electrical network.

A second important motivation for the development of DLC systems has been to facilitate meter reading from a distance. This includes not only electricity meters but also water, gas, and temperature meters. Developments in this direction were started in the United States, where meter reader salaries are relatively high and electricity companies are not allowed to charge their customers fixed monthly amounts, as is usual in Europe (2). Furthermore, an English study has shown that a meter reader achieves an average information rate of only about 1 bit/s (3), which is very low compared to what is possible with DLC systems. This metering information, apart from automatic billing, may be used for customer functions, such as warnings when no pay has been received, or even disconnecting nonpayers.

The utility company may also use the DLC channel to shut off parts of the network in the event of danger, to gather user statistics, to transmit information to selected users, or to broadcast simultaneously to all users.

Home automation and intelligent buildings are currently receiving some attention. Here power line communications can provide a natural communications link for various devices, such as the sensors of an alarm system.

Several investigations have also focused on employing the low-voltage network as a local area network (LAN) for conveniently connecting many different computers in the same building (4,5). Furthermore, digital customer services like e-mail and electronic banking are becoming available using the low- and medium-voltage network as a communication channel.

The question also arises of whether low-voltage networks may be able to carry commercial voice traffic (i.e., telephone conversations) on a limited scale. This application may be of use in developing countries, where situations arise when it is beneficial to employ the same costly cable infrastructure for dual purposes. The feasibility of several voice channels has been demonstrated previously on the high-voltage network (6). On the other hand, the severe impulse and burst noise on the low-voltage network may necessitate the use of a high degree of time diversity, such as deeply interleaved error control codes, leading to time delays not usually acceptable for bidirectional voice communications.

Other applications that seem to be hitherto unexploited include the transmission of slow-scan TV images over long distances. In many countries, this facility may be used for security purposes and for the monitoring of distant installations. In developing countries, such a facility may also be used, in conjunction with an audio channel, to realize educational broadcasts to remote and isolated communities.

ADVANTAGES AND DISADVANTAGES

Power line communications is usually considered as a retrofit facility (i.e., the electrical power reticulation network has already been installed and an advantage is thus that there are no additional costs pertaining to cables and related infrastructure). Also, the power network has the advantage of being an independent communications network.

The high- and medium-voltage networks cover long distances. Furthermore, during the last decade, many electricity companies have set up a fiber-optic network in parallel to the high-voltage network, mainly for signaling purposes. Only a fraction of the capacity of this fiber-optic network is currently used, and it could therefore very well be used to form an extended telecommunications network, together with the DLC systems, operating on the medium- and low-voltage networks. The geographic coverage of the low-voltage network is usually very wide where human habitation exists, and access to the network can be simple.

On the other hand, as stated before, power lines represent a particularly difficult communications environment. Noise levels may be excessive. The cable attenuation at frequencies of interest to communications is usually very large. Repeaters may thus be needed to compensate for cable losses and to bridge over distribution transformers. Standing waves on long cables may lead to nulls in the frequency response. Care should be taken to circumvent the potential problem of large-valued capacitors or inductors that may arise when designing for low-frequency work. Furthermore, electromagnetic compatibility problems arise when interfacing electronic circuits with electrical power lines. To compound matters, important channel parameters, such as impedance and attenuation, as well as the noise levels fluctuate with time and load in a very unpredictable way.

In view of the aforementioned perturbations and difficulties, the goal has thus often been in the past only to achieve a low-rate data communications channel, with speeds up to 2400 B.

STANDARDS

Because of the wide geographical coverage of reticulation networks, coordinating bodies have formulated specifications to restrict the bandwidth and power levels of communications signals, in order to limit interference with other users of low-frequency radio communications.

The power line communications channel is thus nowadays defined to some extent by international or national standards. Perhaps the most important signaling parameters that are specified by these standards are the maximum transmitted power and the allowable bandwidths. These parameters are restricted in order to prohibit or limit interference with other telecommunications services and to prevent further pollution of the electromagnetic spectrum.

Until recently, some countries have had individual standards. For example, in 1974 the Deutsche Bundespost published the *Technische Richtlinie für TF-Funkanlagen für industrielle und gewerbliche zwecke* (7), making provision for 5 mW of transmitted power within one channel covering 30 kHz to 146 kHz.

More weight should be attached to the new European and international standards on which Muller reported in Ref. 8. Perhaps most important for the development of transmission equipment is the European CENELEC 50065.1 standard, which specifies bandwidth and transmitted power (see Fig. 1) and which is now in the process of being accepted by most European countries. The CENELEC 50065.1 specification provides for five different channels in the 3 kHz to 148.5 kHz band, with transmitted power depending on the specific channel and coupling method, but not to exceed 500 mW.

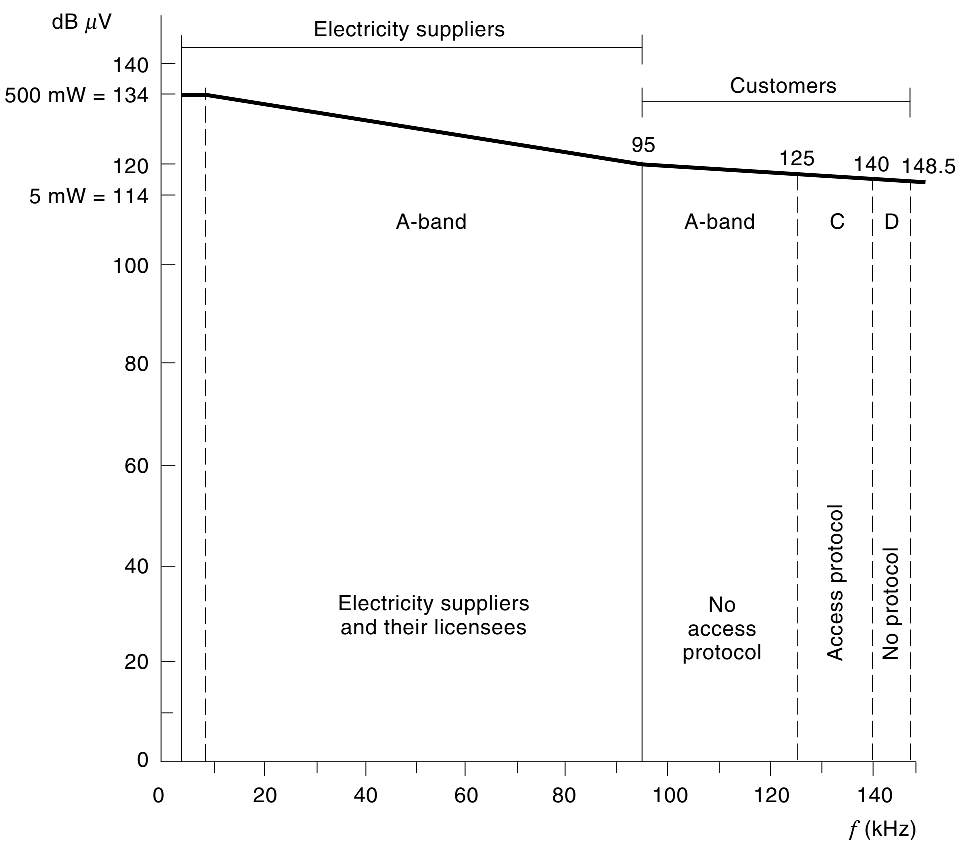

Figure 1. The CENELEC 50065.1 standard makes provision for five different channels in the 3 kHz to 148.5 kHz band, with transmitted power depending on the specific channel.

In North America, the Federal Communications Commission (FCC) regulates transmitted power and bandwidth [0 kHz to 530 kHz (9)].

Standards pertaining to related issues include the IEC 870 international standard on telecontrol, teleprotection, and associated telecommunications for electrical power systems, as well as the IEC 1107 and 1142 standards pertaining to equipment for electrical energy measurement and load control. The CENELEC ENG1107 standard specifies equipment for electrical energy measurement and load control.

On a higher systems level, the DLMS, or Distribution Line Message Specification applies. This is a media-independent application layer protocol that uses a three-layer model to target communication environments with limited resources. (See the IEC TC57 WG9 international standard.)

When considering home automation, the European ESPRIT HS comprehensive communication system for interconnecting several kinds of electronic products used within the home should be considered. This system uses transmission at 2.4 kbit/s over power lines or other channels and provides higher-level systems functions.

THE CHANNEL

Noise and Disturbances

There are many different sources of noise and disturbances on electrical power networks. The prevailing noise has been investigated and characterized, and is well understood as far as nature is concerned. However, on any given channel the noise remains hard to predict.

On high-voltage networks, channel noise may be due to, among other causes, atmospheric or static discharges, low-level corona discharges, lightning, circuit breaker operations, and the transients produced within a power station.

On medium-voltage networks, the on and off switching of capacitor banks used for power factor correction is infamous for causing high noise peaks.

On the notoriously noisy low-voltage network, some of the foregoing may also contribute noise (although the medium-/low-voltage transformers are effective filters), but the worst offenders are the various household devices and office equipment connected to the network.

According to Ref. 10, the noise and disturbances on the electrical power network can be broadly classified as discussed in the following subsections.

Waveshape Disturbances. Waveshape disturbances include

1. Overvoltages, which may be classified as persistent (≥ 2 s) or surges (<2 s)
2. Undervoltages, which may again be classified as persistent or surges
3. Outages
4. Frequency variations
5. Harmonic distortions

Superimposed Disturbances. Superimposed disturbances may be subdivided as follows:

1. Persistent oscillations, which may be either coherent or random (stationary or nonstationary)
2. Transient disturbances, which include impulses and damped oscillations

Considering the waveform disturbances, one can remark that in many developed countries these are of little importance, because the electicity supply companies succeed well in keeping their generated sinewave clear. Small disturbances of overvoltages and undervoltages do not influence the transmission of information. However, transmitters and receivers should be developed in such a way that they can cope with these disturbances. Outages can be subdivided into two subclasses: The first is outages caused by line breakage. Naturally, in this case information transmission over the power line is impossible. The second subclass includes outages caused by a failure in, for example, a transformer, leaving the lines intact and therefore having no impact on the communication conditions. Frequency variations can be a severe problem: Many DLC systems base the synchronization between transmitter and receiver on the generated sine wave. (In Europe and elsewhere, the generated sinewave has frequency 50 Hz, and in North America and elsewhere it has frequency 60 Hz.) Jitter in this sinewave can therefore cause synchronization errors, especially when the bit rate on the channel (chip rate in case of a direct sequence spread spectrum system) is high. Finally, higher harmonics of the generated sinewave, caused by nonlinearities introduced by switches and filters, can be a major source of disturbances, although the biggest part of the energy is located at frequencies below the CENELEC A-band.

Whereas the electricity supply companies are responsible for waveshape disturbances, superimposed disturbances are mostly caused by their clients or, more precisely, by a number of the clients' appliances. These disturbances are mostly due to the fact that certain appliances are not filtered well enough. Large factories with extensive plant or machinery can cause much noise of this class on the medium-voltage network. This is one of the reasons why such factories often have their own high-/medium-voltage and medium-/low-voltage transformers, which are filters in themselves. On the low-voltage network, a number of household appliances are also known for superimposed disturbances noise.

The classification of the noise and disturbances as given by Ref. 10 is a general one. When analyzing the noise on low-voltage networks in private home environments for the development of a DLC system, some refinements to the classification can be made. Since the generated sinewave exhibits a certain jitter, the entire class of waveshape disturbances given by Ref. 10 can be left out of consideration. According to Dostert (11) this jitter has a worst-case mean value of 35 μs and a standard deviation of 25 μs.

Superimposed disturbances due to Ref. 10 can be used with some minor adaptations for the analysis of the low-voltage network as a communications channel. DLC systems usually have a relatively low data rate. Consequently, impulse noise and damped oscillatory noise both usually result in only single bit errors (12). Therefore, both can be considered to be impulse noise. This fact, among others, leads to a classification of noise in the low-voltage network such as the one given by Vines et al. (13), which is better suited for DLC-communication analysis:

A. Noise having line components synchronous with the power system frequency

B. Noise with a smooth spectrum
C. Single-event impulse noise
D. Nonsynchronous noise

Noise Having Line Components Synchronous with the Power System Frequency. The most important source that produces this kind of noise (hereafter called type A noise according to the classification made by Vines) is the so-called triacs or silicon-controlled rectifiers (SCR). They are often found in light dimmers, which employ triacs to “switch off” the appliance connected for a fraction of the generated sinewave.

Light dimmers are very popular as a cheap way to make the light intensity of light bulbs and termo luminance lamps continuously variable. The noise characteristics of a dimmer are examined in Ref. 13. The light dimmer is connected in series with the load (e.g., a 100 W light bulb) and controls the intensity of the light by the very fast on and off switching of the filament. This switching is controlled by the generated ac voltage. As soon as this voltage reaches a certain level during the positive cycle of the sinewave, the triac switches on/off. The same is the case during the negative cycle of the sinewave, resulting in a double frequency (i.e., 100 Hz or 120 Hz periodic switching). This switching (dv/dt 100 V/μs) causes noise with high frequencies on the net voltage. Because this noise occurs periodically with a frequency of 100 Hz (or 120 Hz), it follows from the Fourier series representation of periodic signals that the spectrum of this noise consists of a series of harmonics of the 100 Hz (or 120 Hz) fundamental component. Which harmonics dominate is primarily determined by two parameters:

- The natural resonance frequency of the circuit formed by light dimmer and load
- The settings of the dimmer

The amplitude of the spectral lines depends on the load. A 400 W lamp, for example, causes higher spectral lines than a 100 W lamp.

Another important source of class A noise, according to Chan and Donaldson (14), are photocopiers, which also generate strong noise impulses at twice the power system frequency rate.

There are three apparent ways to combat this kind of noise:

- The frequency spectrum of typical class A noise is very regular, having peaks at the double frequency harmonics. In principle, successful communication may be possible with modulation or line coding schemes, with nulls at these harmonic frequencies.
- Tengdin (15) proposes sin x/x filters at the input of the receiver, with spectral nulls at multiples of the power system frequency, in order to attenuate the noise line components. It should be kept in mind, however, that these filters may also attenuate some of the signal energy.
- Considering the time domain representation of the signal, it can be seen that, at equal intervals of 1/100 s (or 120 s), a noise pulse can be expected. The effect of errors caused by these impulses can be eliminated by a fairly simple (and thus inexpensive) time division multiplexing scheme, aided by a forward error-correcting code.

Noise with a Smooth Spectrum. The most important source of noise with a smooth spectrum (hereafter called type B noise according to the classification made by Vines) are universal motors.

Universal motors are small motors with serial windings that function with either a dc or an ac voltage supply. Because of their relatively small dimensions and weight, they can be found in numerous household appliances, like vacuum cleaners, mixers, blenders, and power tools. The noise they produce is caused by the brushes inside the motor, which provide a contact between the rotating and stationary parts of the motor. This noise has a relatively flat spectrum in the frequency range to be used by the DLC system (i.e., the CENELEC A-band in Europe). Therefore, it can be modeled as band-limited white noise, having a power spectral density that is often larger than that of type A noise.

Similar to many other communication systems, the low-voltage network also exhibits additive white Gaussian noise. However, the power spectral density of this so-called background noise lies, according to Ref. 16, typically 22 dB underneath that of noise type A and is therefore of little concern.

A characteristic of most of the appliances that have universal motors inside them is the fact that they are often used for a short period of time. This implies that when the DLC communication system does not have to function in real time, the effect of class B noise is reduced and can, in fact, sometimes be neglected (apart from the ever-present background noise) when some kind of automatic repeat request (ARQ) system with error control coding is implemented. Alternatively, the system may have to be designed to cope with the worst-case type B noise. It is interesting to note that the average noise caused by universal motors in Japan, according to Ref. 17, lies in summer about 10 dB to 15 dB higher than is the case during the winter. This is caused by the fact that during summer, many cooling appliances, like air conditioners, are switched on.

Single-Event Impulse Noise. Single-event impulse noise (type C noise) is primarily caused by switching phenomena like lightning and the switching of thermostats. Type C noise disturbs the entire frequency band for a small fraction of the time. These noise impulses may, in reality, be damped oscillations. However, compared to the relatively low bit rates employed by DLC systems, this noise can be modeled as impulses.

The parameters with which the impulses can be characterized are, according to Chan and Donaldson (14)

- Amplitude probability distribution (APD)
- Impulse width distribution (IWD)
- Impulse interval distribution

Some detailed measurement results are also given in Ref. 14.

Experience with impulse noise in other communications environments has shown that the effect of type C noise can be overcome by applying an appropriate error-correcting code, perhaps combined with interleaving.

Nonsynchronous Noise. Nonsynchronous noise (type D noise) is characterized by periodic noise pulses that occur with a frequency other than multiples of the net voltage. The major source of type D noise is television sets, but in the last few years, computer monitors have become an important source of type D noise.

A television picture is built up of left-to-right lines, which are usually scanned in 53.5 μs. After scanning, the trace returns from the right to the left side of the screen in 10 μs; this is called a horizontal retrace. During this retrace, no information (i.e., black) is written on the screen. Therefore, for the scanning of one image line, approximately 63.5 μs is needed. Synchronization is realized by a 5 μs pulse, superimposed on the horizontal retrace. It is this pulse, which occurs every 63.5 μs (i.e., with a frequency of 15.734 kHz), that causes the type D noise. In general, one can say that every television set produces strong noise components around 15.734 kHz and its higher harmonics.

This noise caused by television sets can be avoided if the transmitted information signal has no energy at the aforementioned frequencies. During the last decades, however, with the prevalence of personal computers, a wide variety of computer monitors have come onto the market, employing other line frequencies than the 15.734 kHz described previously. Therefore, when developing a DLC system, the television line frequency of 15.734 kHz and its higher harmonics should be avoided by the modulated signal and some kind of frequency diversity should be applied to avoid the destructive effects of computer monitor line frequencies.

In the previous paragraphs, a qualitative description of noise on the low-voltage network was given. Although it would be a mistake to develop a DLC system not knowing the quantitative noise characteristics, some suggestions can be made at this stage for the development of a DLC system:

- Forward error-correcting codes combined with interleaving (to provide time diversity) should be implemented to cope with noise types A, B, and C.
- The television line frequency and its higher harmonics should be avoided when modulating the signal onto the channel: No signal information should be transmitted at these frequencies.
- Some kind of frequency diversity (e.g., frequency hopping) combined with forward error correction should be implemented to be able to cope with the unknown line frequencies of computer monitors.

In almost all systems proposed in the literature and/or available on the market, one or more of the aforementioned recommendations have been implemented.

Some results of experimental noise measurements are presented in Fig. 2.

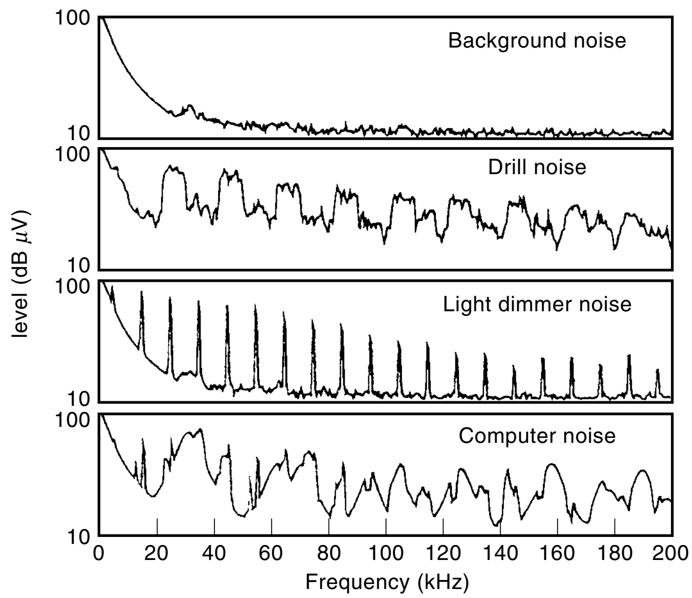

Figure 2. Experimental measurements of the power spectral densities of noise due to various sources.

Channel Impedance

When developing a DLC system, accurate knowledge of the channel impedance is required. One reason for this is the fact that the signal power at the receiver side reaches a maximum when the impedances of transmitter, receiver, and channel are matched.

The impedance of the low-voltage network depends strongly on the point of measurement. This is due to the fact that the power network is a widely spread network, with the medium-/low-voltage transformer's secondary (with its own impedance) as the driving force and many loads connected in parallel.

From this observation, it can already be seen that channel impedance is a strongly fluctuating variable, depending on specific loads being connected to the net at specific times. Although this results in the fact that a single value for the channel impedance can seldom be given, it is still possible to indicate a range within which the impedance fluctuates with a large probability.

Schaap (18) quotes rough figures of 0.1 Ω to 2 Ω for low-voltage networks and 10 Ω to 150 Ω for medium-voltage networks.

In Ref. 19 the results of several impedance measurements in Europe are reported (see Fig. 3) From these, an impedance magnitude range of 0 Ω to 80 Ω for the frequency range of interest can be concluded. Also, from these measurements, a frequency dependency of the mean impedance, represented by $|Z| = 0.005 f^{0.63}$, can be determined.

Typical real and imginary impedance components as a function of frequency are depicted in Fig. 4.

According to Vines (20) the overall impedance of a low-voltage network results from

1. The impedance of the medium-/low-voltage distribution transformer
2. The characteristic impedance of the cables used
3. The impedance of the devices connected to the network

We now briefly discuss the aforementioned factors.

Impedance of the Distribution Transformer. In Ref. 21 O'Neal gives a theoretical analysis of distribution transformers. Some measurements of the y-parameters at frequencies of interest are also discussed. In Ref. 20, Vines gives the results of an impedance measurement on a number of distribution transformers, which confirms that the impedance of the sec-

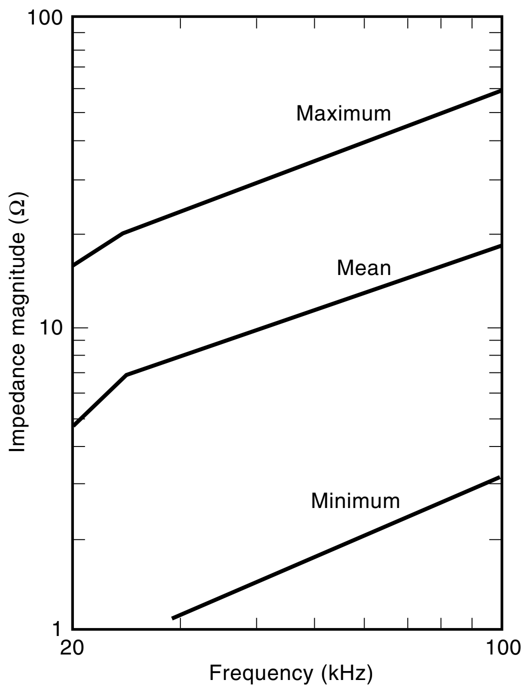

Figure 3. Example of magnitude of power line impedance as a function of frequency, as obtained in West Germany (19) for the CENELEC A-band.

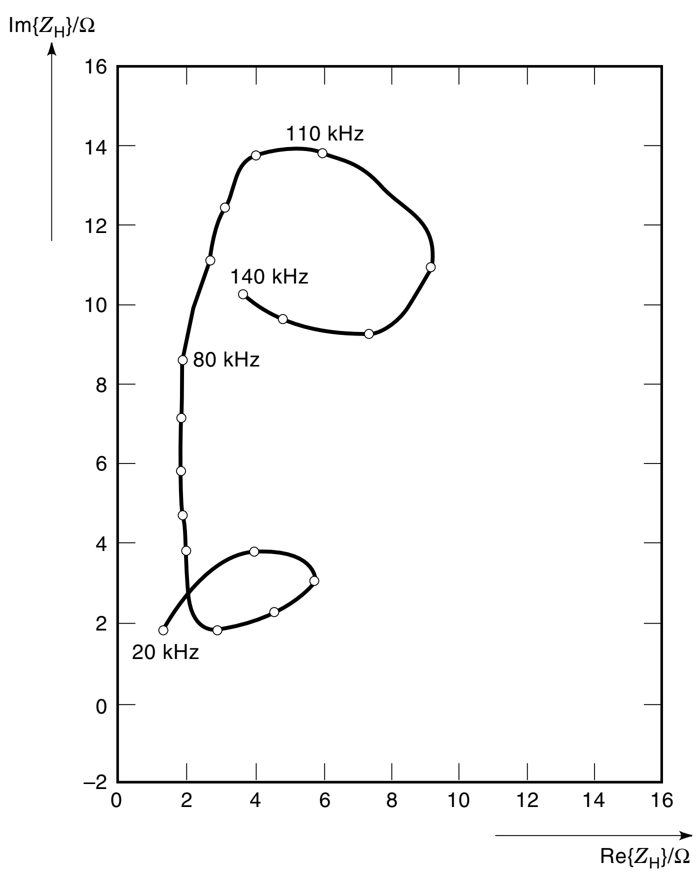

Figure 4. Real and imaginary impedance components as a function of frequency, obtained by Dostert (23) in a university laboratory.

ondary increases with frequency. However, this dependency tends to get smaller for larger transformers.

Within the transformer, the various phases are coupled, resulting in a signal flow from one phase to another. This means that, in principle, it is possible to transmit a signal across phases without the use of coupling circuits between phases.

Characteristic Impedance of the Cables Used. A wide variety of underground and above-ground cables is used in different low-voltage networks; thus it is impossible to predict the channel impedance. According to Ref. 21, cable capacitances in the frequency range of interest are much smaller than the transformer's capacitance. Therefore, cables can be modeled as a serial connection of inductors and resistors. In Ref. 19, the value of the characteristic impedance is indicated to vary between 70 Ω and 100 Ω.

Impedance of the Devices Connected to the Network. Typical impedance values for household appliances in a 220 V network vary between 800 Ω for a 60 W light bulb and 35 Ω for a 1400 W vacuum cleaner. Heavy load appliances, connected between two phases, can exhibit impedance values that are much smaller, like 32 Ω for a water heater or 12 Ω for an electrical heater.

As already indicated, the overall impedance of a low-voltage network results from a parallel connection of all the network's loads. This means that especially the small impedances play a dominant role in the overall impedance.

Signal Attenuation

The often very low impedance of the low-voltage network causes high signal attenuations. The time variations of this impedance, which lead to mismatches in transmitter, channel, and receiver impedance, contribute to the attenuation, rendering it also time variant. Rough figures for the signal attenuation are given by Schaap (18). For the low-voltage network, this amounts to 100 dB/km, and for the medium-voltage network to 10 dB/km.

The large attenuation on low-voltage networks may necessitate the frequent use of repeaters, at distances of less than 1 km. High-voltage networks are much more favorable, and distances of several hundred kilometers have been achieved without repeaters (6). It should also be stated that transmit power levels of up to 40 W or 80 W were used.

Some attenuation measurements on the low-voltage network are presented in Fig. 5.

In Ref. 22 an analysis of the signal attenuation on medium-voltage networks is given. We now briefly give an overview of factors that determine signal attenuation.

Time Dependency of Signal Attenuation. There is a close relationship between network impedance and signal attenuation. The same time dependencies of the network impedance can therefore be considered when investigating the signal attenuation. The fact that many appliances are only connected to the network during the day causes, for instance, a strong day/night sensitivity (23,24).

Frequency Dependency of Signal Attenuation. In Ref. 25 measurements on Canadian low-voltage networks are reported,

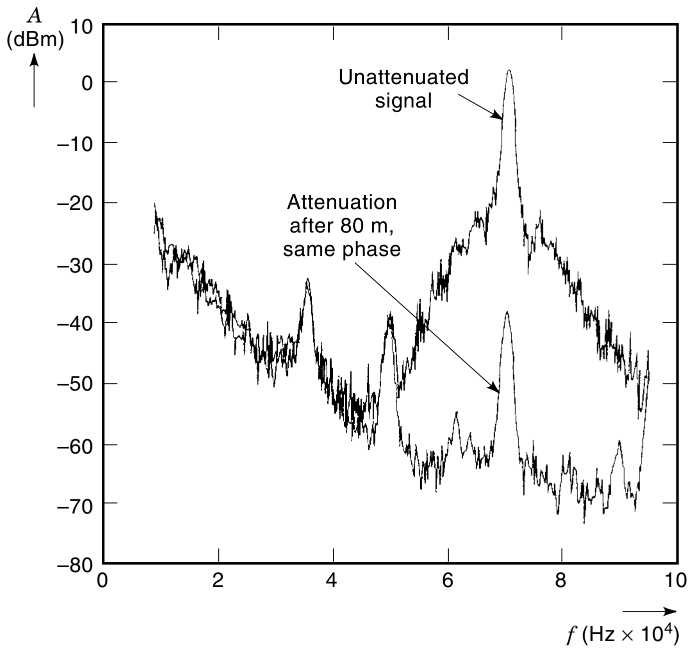

Figure 5. Experimental measurement of the attenuation of a phase shift keyed (PSK) signal in the distribution network.

and the conclusion is drawn that in this study for frequencies below 100 kHz, signal attenuation is independent of frequency. For frequencies above 100 kHz, an attenuation increase of 0.25 dB/kHz is reported.

Due to transmission line effects in long (>400 m) cables, signal attenuation can get very high at certain frequencies.

Distance Dependency of Signal Attenuation. In principle, the attenuation depends linearly on distance, as long as no loads are connected between transmitter and receiver. However, normally many loads are connected to the net between transmitter and receiver. In practical situations, a worst-case signal attenuation of 100 dB/km is often taken.

Signal Attenuation Over Network Phases. The signal attenuation between two network phases depends strongly on the impedance between those phases. However, according to Chan (23), the signal attenuation between two points connected to the same phase is normally smaller than the signal attenuation between two points at the same distance connected to different phases. This difference, nevertheless, can be small compared to the absolute attenuation.

According to O'Neal (16), attenuation across phases usually varies between 2 dB and 15 dB. However, in some extreme cases, values of almost 40 dB were also measured.

Channel Models

As stated before, channel parameters vary with time, load, frequency, and so on. It is therefore difficult to determine accurate channel models. Time dependency is especially hard to model.

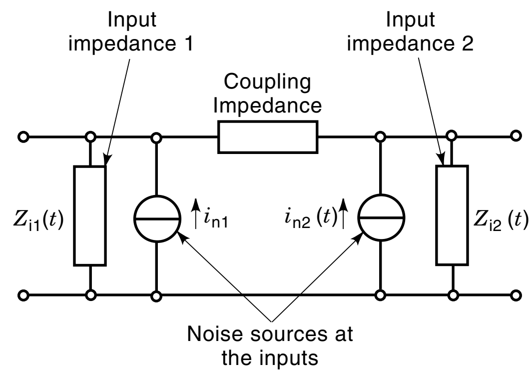

Figure 6. Linear systems channel model proposed by Dostert (23).

Dostert (24) proposes the circuit theoretical model shown in Fig. 6. The channel model in Fig. 7 is due to Onunga and Donaldson (4). Briefly, the filter response $H(f,t)$ varies to reflect the change in electrical loads, while $A(t)$ represents fading and is often periodic. The factor B represents the fading level of the noise relative to the signal.

The fact that in both models all elements are time dependent in a way that is largely uncertain indicates that it is very difficult to develop accurate channel models.

OTHER COMMUNICATIONS CONSIDERATIONS

Coupling the Signal onto the Channel

There are various ways to couple communications signals to three-phase electrical power networks. As pointed out by Van der Laan (26), there are several closed current paths that may be considered. Basically, these can be divided into two main categories:

- In the case of *differential mode* coupling, the line wire is used as one terminal and the neutral wire is used as the second terminal. This mode can thus only be used when a neutral wire is present. In low-voltage networks, this is normally the case, but in medium- and high-voltage networks, often a seperate neutral line is not present. In this case the ground line can be used as a second terminal.

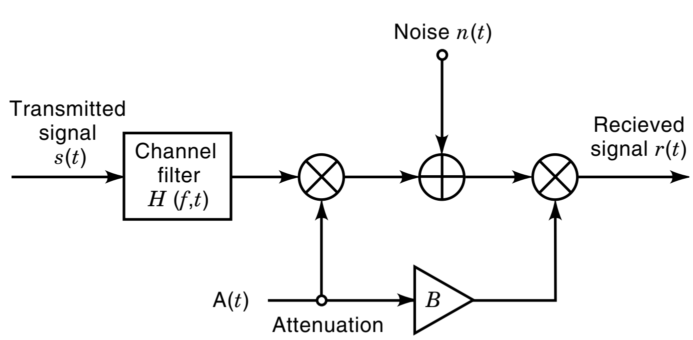

Figure 7. Channel model with noise proposed by Onunga and Donaldson (4). Briefly, the filter response $H(f,t)$ varies to reflect the change in electrical loads, while $A(t)$ represents fading and is often periodic. The factor B represents the fading level of the noise relative to the signal.

- In the case of *common mode* coupling, the line and neutral wires are used together, forming one terminal, and the ground wire serves as the second terminal. Theoretically, this coupling mode cannot work because neutral and ground wires are connected at the transformer. In practical situations, however, the inductance between the points of coupling and the short circuit point is large enough to circumvent this problem. This coupling mode is known to yield up to 30 dB better coupling than differential mode coupling. In some countries, common mode coupling is not allowed on low-voltage networks, due to potential dangers for the customers. In other cases, care should be taken that the input current does not exceed the sensitivity of the earth leakage protection devices, usually 30 mA for low-voltage applications.

In a two- or three-phase electrical power network, common or differential mode coupling can be performed in parallel for all phases at the same time, when these phases are available at the transmitter side. This, of course, is better than relying on the natural coupling between phases on the transformer side and at devices that use more than one phase for power supply, as described in the previous section.

Looking at the physical implementation of the coupling, two ways of connecting the DLC unit to the network are possible:

- The first is known as *capacitive coupling*. A capacitor is responsible for the actual coupling, and the signal is modulated onto the network's voltage waveform.
- The second is known as *inductive coupling*. An inductor is used to couple the signal onto the network's current waveform.

Inductive coupling is known to be rather lossy. However, no physical connection to the network has to be made, which makes it safer to install than capacitive coupling. These observations make clear, why in the low-voltage network, given the power restrictions, normally only capacitive coupling is used, whereas in the medium-voltage network both methods are used.

Transmitted Power

Electrical power reticulation networks can be viewed as large antennas. This indicates that, also due to the wide geography covered, special care should be taken to limit interference to other users. Consequently, the transmitted power should be restricted. A further reason to restrict transmitted power levels is the inadvertent contamination of the generated sinewave provided by the utility to other users of electrical energy.

Consequently, a low level of allowable transmitted power is nowadays preferred for DLC systems (e.g., 5 mW in the Deutsche Bundespost specification, and not more than 500 mW in the CENELEC specification, depending on band and coupling, as indicated in Fig. 1). Whether or not a transmitter exceeds the 500 mW CENELEC specification is measured with the help of a reference circuit, which consists of a 50 Ω resistor, connected parallel to a 50 μH inductor and a 1.6 Ω resistor in series.

Bandwidth

The power limitations discussed in the previous section, were introduced to prevent DLC systems from interfering with other communication systems. Similarly, to prevent excessive interference from noise and other communication systems on a DLC transmission, transmission should take place in a relatively quiet part of the electromagnetic spectrum.

At low frequencies (<1 kHZ), power line noise components, originating from higher harmonics of the network voltage frequency, are relatively high. The range from 1 kHz to 3 kHz is used by ripple control systems. On the other hand, at the higher-frequency end of the available band, the most important other users of low-frequency electromagnetic waves include LW (long wave) and MW (medium wave) radio broadcasts, as well as certain navigational radio facilities. Consequently, in Europe, the higher limit on the transmission band is set to prohibit interference with LW radio at 150 kHz. Only MW or AM broadcasts need to be considered in the United States and Japan. These start at 535 kHz and typically use an intermediate frequency of 455 kHz. Consequently, in the United States a spread spectrum signal is set to fit between 100 kHz and 450 kHz (5).

In Europe, the Deutsche Bundespost specifies one channel covering 30 kHz to 146 kHz. The CENELEC 50065.1 specification provides for various channels, spanning 3 kHz to 148.5 kHz. Broadly speaking, the A-band covering 3 kHz to 95 kHz is reserved for the utility companies, with DLMS as candidate protocol. In this band, communication between customers' households and a central point, mostly the medium-/low-voltage transformer, is performed. The CENELEC B-, C-, and D-bands covering 95 kHz to 148.5 kHz are reserved for end-user applications, with the HS as candidate protocol in the C-band. In these bands, applications such as baby intercoms (B-band) and local area networks for computers (C-band) are projected. Refer to Fig. 1 for more information.

Electromagnetic Compatibility Problems

To establish power line communications links, sensitive electronic devices need to be hooked up to power lines having severe perturbations and carrying voltages far outside the input ranges of these electronic devices. To prevent malfunction, or even damage, electromagnetic compatibility (EMC) problems should also be considered.

Van der Laan gives a treatise on this subject in Ref. 26. He considered disturbances such as transients, voltage fluctuations and harmonics. Reference can be made to the CBEMA curve (Fig. 8), developed by the Computer and Business Equipment Manufacturers Association, for electronic power supplies, as a guide for specifying acceptable voltage limits. Referring to the acceptable operating envelope in Fig. 9, electronic equipment should function normally as long as disturbances stay within these limits. Perturbations contributing to operation outside the envelope may include impulses, waveshape faults, voltage swells, and sags. From an EMC point of view, Van der Laan classifies disturbances into transients, voltage fluctuations, and harmonics.

Transients are the most important. Especially on the medium-voltage network, they may lead to large, violent disturbances, which make electronic limiters, with their accompanying nonlinear effects, necessary. In fact, nonlinearity is unavoidable in the case of large transients. When the inputs

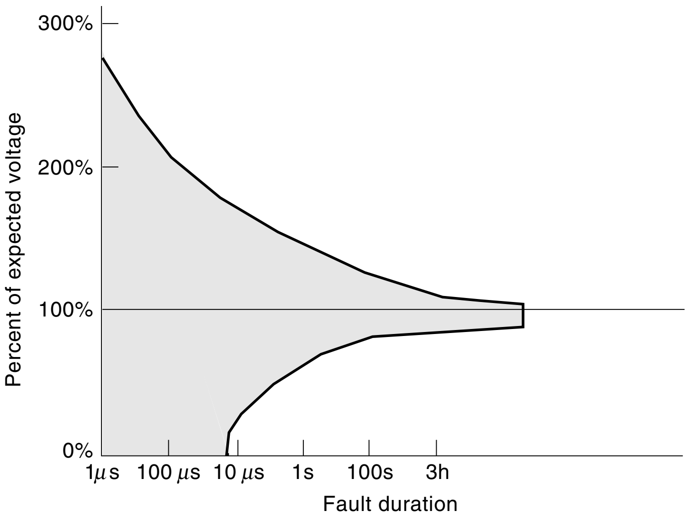

Figure 8. CBEMA curve, which can be used as a guide for specifying voltage limits acceptable for disturbances.

of electronic devices are driven into the nonlinear region, these inputs may become temporarily inactive, digital levels may be changed, and even permanent damage can result. For DLC systems operating on the low-voltage network, limiters would make the units too expensive. In these cases, filtering networks, made of passive elements only, normally protect the vulnerable electronics sufficiently.

A limiter with typical v-i characteristic, as shown in Fig. 9, can be used to protect electronics. While the abrupt transition in the v-i curve is good for limiting safety, this nonlinearity may also generate harmonic frequencies, sum and difference frequencies, and dc shifts. The Fourier analysis as analytical tool is rendered useless since it cannot explain the new frequencies.

In conclusion, Van der Laan suggests concentrating on the front end in order to keep disturbances away from electronics. As diversion, one or more filters with passive L, C, and R components, restricted to the frequency band of the signal, should precede the limiter. Limiters, which also have a finite life, should be used as little as possible. Future research work may include the collection of statistics on remaining disturbances at the output of the front end, in order to optimize the design.

COMMUNICATION SYSTEMS AND SOLUTIONS

Several different communication solutions have been proposed, and various commercial systems are available. The most appropriate solution depends on the application, which in the case of digital communication systems dictates the transmission rate and error probability and which determines whether the system complexity and resulting cost is warranted. For example, communication systems providing for monthly meter readings at residential customers and communication systems realizing local area networks for computers have different economical considerations.

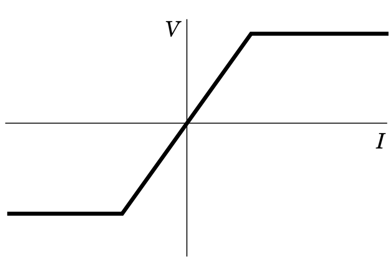

Figure 9. Simple nonlinear limiter that can be used to protect electronics coupled to power lines.

The earliest systems were fixed carrier, analog systems. Several systems providing voice communications over the high-voltage network, still work on this principle. Among these are the Westinghouse system (27), which provides 12 voice channels of bandwidth 2.7 kHz. It uses single side-band amplitude modulation at 10 W or 20 W, in an 8 kHz to 136 kHz power line channel. This system is intended for rural telephony. Similarly, the ABB system (6) has a 40 W or 80 W output, providing up to four 3.3 kHz wide voice channels, using a carrier frequency programmable from 40 kHz to 500 kHz. Both of these systems make provision for data communications at up to 2400 baud with a suitable modem. ABB reports a range of several hundred kilometers, without using repeaters.

At the lower end of digital communication solutions, narrowband FSK and ASK have been proposed as modulation schemes. Adaptive FSK schemes, operating in one of several potential frequency bands, can overcome frequency selective fading, due to standing waves. These occur at frequencies difficult to predict. Philips and Signetics produce an integrated circuit (i.e., the NE5050 power line modem) that affords some immunity against power line noise and with which an ASK or FSK modem can be realized.

At the higher end of digital communications solutions, spread spectrum systems are widely considered as an effective communications solution to overcome the many frequency selective perturbations on power lines. A number of such systems have been reported in the literature, and 19 such papers are listed in our Bibliography. Both direct sequence and frequency hopping systems have been considered. Several authors reported on spread-spectrum systems. As an example of contemporary systems, we now briefly give an overview of some European systems as reported in Ref. 28.

Hertel from Echelon GmbH describes the LONWORKS technology in Ref. 9. This technology is based on the Toshiba 3120/3150 neuron chips, with which the author created a local operating network (LON), which may function on the DLC channel or on other channels. Transmission is realized by means of transceiver modules, implementing a 31 chips/bit spread spectrum system and with which 2 kbit/s transmission can be realized in the CENELEC A-band. Employing packet switching and using the OSI seven-layer protocol, sophisticated network functions can be realized.

Dostert gives an overview of power line communications in Ref. 24. In this paper, as well as in earlier work (11,29–31), he reports on results obtained with frequency-hopping spread spectrum systems. These include results on indoor networks, where he transmitted 300 bit/s at a hopping rate of 900 s^{-1}, employing 0.35 V_{rms} in the spectral range 30 kHz to 146 kHz. Similar results involved outdoors networks, where 60 bit/s was transmitted at a hopping rate of 300 s^{-1}, employing 0.35 V_{rms} to 1 V_{rms} in the same spectral range. A bit error rate of order 10^{-6} was achievable.

Schaap (18), from Datawatt BV, describes the Robust Communications (ROBCOM) System for low- or medium-voltage networks. This system also employs frequency hopping in the 20 kHz to 95 kHz band, transmitting up to 0.5 W. Differential phase shift keying is employed as a modulation scheme, and a data rate of 1000 bps is achieved. Error control coding includes convolutional codes with interleaving for error correction, followed by a 45 bit CRC block code to do error detection with undetected error probability, 10^{-12}. The system also provides advanced automatic network functions.

Lehman (32) from ZAM eV, proposes the use of direct sequence spread spectrum, specifically CDMA/SSMA, to overcome the dispersion problems in a cable network, which are hard to model. Data rates of 2400 bit/s and even 9600 bit/s in some tests were achieved.

The preceding discussion provided a brief report on some current European spread spectrum systems. Reference can be made to our Bibliography for some information on North American or Japanese spread spectrum systems. In the wider available channel bandwidth of 10 kHz to 450 kHz, data rates of 9600 bit/s have been reported (9,33,34), and even 19.2 kbit/s with an error rate of 10^{-9} km up to 4 km (5).

It is interesting to note the consensus in the literature that efficient power line communications are impossible without error control coding. In addition to ROBCOM's two-level approach to error correction and residual error detection, many other coding schemes have been employed. For example, Tengdin (15) proposes interleaving the (24,12) Golay code to degree $\lambda = 5$, in order to correct bursts of 15 bits or 500 ms duration on a 30 B channel. Friedman et al. (35) propose $R = 1/2$ self-orthogonal convolutional codes with majority logic decoding, correcting up to $t = 4$ errors, with $\lambda = 7$. Depending on the modulation scheme and transmission rate, many other error control schemes can be found in the literature.

Although spread spectrum signaling is often considered as an effective scheme to communicate over this channel, it should be noted that the frequency selective perturbations on the channel are more deterministic than on the channels for which spread spectrum schemes were originally developed. Also, the limited available bandwidth restricts the processing gain.

It is still an open question whether wide-band signaling schemes with better performance than spread spectrum systems can be developed for this channel. Also, the economy of certain low data rate applications, such as meter readings, encourages the development of simple signaling schemes with lower complexity than spread spectrum systems and better performance than current low-end solutions.

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