Power Delivery Infrastructure Differences and Their Impacts on Different Types of Power Line Communications for Automatic Meter Reading

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Automatic Meter Reading (AMR) is making fast inroads into the electric utility industry, primarily triggered by the possibilities of instituting retail wheeling in the present deregulated environment. Meters have to be read more often and faster and new businesses open to provide meter reading and billing services to the various electric distribution companies. To make it possible, a communication system is required that links every electric energy metering device to several metering data collecting computers in a two way fashion. The metering data have to be gathered at regular intervals, dated and time stamped. This will allow the billing service company to determine how much to bill the energy user and to apportion the collected revenues to the various energy providers. The collected data also provide valuable energy usage profiles of the various types of customers. They can be used for projecting demand, pricing strategies, etc.

One of the most attractive options facing the electric industry is to use the power line for communication medium. The modern day vast distribution network reaches practically every home, commercial and industrial sites. A communication infrastructure overlaying the power delivery infrastructure would greatly reduce investment costs for communication network. However, distribution networks in many different countries of the world are quite often different in terms of design philosophy and operating practices. To some extent differences also exist within the same country.

Power line carrier technologies typically operate at the medium voltage network and low voltage networks. Studies and field experiments have indicated that some communication technologies operate real well in one type of network. Other types of technologies may not perform very well in other types of network unless expensive solutions are found. The physical components of the network and the physical configuration of the circuits may create problems to certain power line carrier type of technology. Capacitor banks and underground cables cause heavy signal attenuation at the medium and high frequency ranges. The electric power networks are designed for optimum delivery of power at 50 Hz or 60 Hz. Sometimes circuit lengths are the cause of problems of an entirely different nature. The technology has to deal with standing wave problems, communication cross talk, etc.

Since communication will be the backbone of the Automatic Meter Reading system, there are specific requirements that the communication technology has to meet. A typical AMR system requires hourly meter reading at each customer. Massive amount of data has to be dated and time stamped. With the possibilities that outages may occur in the electric network, attention has to be paid that no data and time information is lost. Differences in generic network design will be highlighted and the impact on the power line communication will be discussed at length. Solutions to problems are available, but sometimes at what costs. The starting technology that is best suited for a certain network environment should be based on a good understanding about the propagation characteristics of the communication signals. Communication reliability, data integrity and security during transmission, effects of outages, spill over and cross talk issues, standing wave problems and the ability to reach every point in the network in a timely fashion, network reconfiguration, etc. are all items that require full attention. Mistakes are made by assuming that one type of communication technology can be transported from one type of network into another different type of network. Due considerations have to be given to the propagation characteristics of the power network and the operational mode of the communication system design.
POWER DELIVERY INFRASTRUCTURE DIFFERENCES AND THEIR IMPACT ON DIFFERENT TYPES OF POWER LINE COMMUNICATIONS FOR AUTOMATIC METER READING

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ABSTRACT
Automatic Meter Reading (AMR) is making inroads into the electric utility industry, triggered primarily by the possibilities of instituting retail wheeling in the present deregulated environment. Meters have to be read more often, faster and time stamped for apportioning the bills of individual customers to the various electric energy retailers.

For many years many companies have investigated the possibility to use the electric distribution network for a communication medium. Several types of communication technologies are already being marketed and installed. Some are still at a pilot and experimental stage and some are already fully operational. In this paper, the RF network and the wired broadband networks are excluded. In view of the different distribution network configurations and operating philosophies in different countries or even within the same country, one should anticipate problems transporting one communication technology that operates well in one type of network to a different type of network. This paper explores the various factors that require serious considerations before adopting a certain technology for its application to Automatic Meter Reading.

INTRODUCTION
Many countries are moving to deregulate and privatize the electric power utility industry. The normally vertically integrated company structure, comprising generation, transmission and distribution of electric power, are now broken into separate generating, transmission and distribution companies. The creation of this new environment is purported to break up monopolies and allows a healthier competitive business environment to benefit the consumers. Electric energy starts to lose its social connotation and is slowly being accepted as a commodity. New business concepts such as “retail wheeling”, “independent electric billing services”, etc. are seriously considered by many because of recent advances in the communication and computer technologies.

Retail wheeling also poses specific requirements on metering, its timely reading and time resolution of the data for accurate billing and apportioning of revenues to the various electric energy retailers. The ideal case is that one should be able to obtain metering data from all electricity users instantaneously with zero time delay on demand data from all electricity users instantaneously with zero time delay on demand.

Manual reading cannot accomplish this task. However one realizes that even with the use of fast communication systems, time delays do occur due to communication, information processing, etc. One possible solution is to append the time information to the energy consumption data when the meter is read. This concept of “time stamping” of metering data also opens the door to other possible applications. Customer profiling, determination of coincidence demand and variable rate designs are just a few possible applications.

GENERAL OPERATIONAL ISSUES
a. The Meter Reading Process
If one can assume that electric users have a choice from which retailer to buy electric energy, then the billing begins at the time the contract starts until the time the contract expires. In the ideal case, the meter is read at the moment the billing starts and at the moment the billing ends. For each customer the electric meter at a customer premise is read at the times $T_1$ and $T_2$ as indicated in Fig.1. The energy consumed is then equal to $(P_2 - P_1)$ kilowatthours. From a practical standpoint the difficulty will be to read all the meters at the same moments $T_1$ and $T_2$ because of the large numbers of meters scattered over a large geographic area.

However, remote meter reading technologies are now available to make it possible to read large number of electric energy meters within a short time. Since energy consumption is continuous with time, delays due to communication and data processing can cause problems in the monitoring of the exact energy consumption of each customer. If the remote intelligent device at the meter has its own real time clock, a command can be issued to obtain the meter readings at $T_1$ and $T_2$ and to store them in local memory. The readings $P_1$ and $P_2$ can be retrieved later on after the time $T_2$. To reduce the time dependency of the metering data retrieval, the remote intelligent device can be designed to store more meter reading intervals. Suppose a time interval $\Delta T$ is defined and the meter is read at the
following times \((T+\Delta T), (T+2\Delta T), (T+3\Delta T), \ldots\ldots, (T+n\Delta T)\). If the number of bins in memory is limited to \(n\), then if the time is incremented by an amount of time \(\Delta T\), the meter reading data at \((T+\Delta T)\) is erased and the memory content is replaced by meter readings at the following times \((T+2\Delta T), (T+3\Delta T), \ldots\ldots, (T+(n+1)\Delta T)\). In order not to lose any meter reading data, all the memory content has to be retrieved during a time between \((T+n\Delta T)\) and \([T+(n+1)\Delta T]\). Several years ago a time interval of \(\Delta T = 15\) minutes was deemed necessary to obtain the required billing accuracy. However this requirement will lead to massive amounts of data transfer, storage and processing. The most recent trend is to adopt a more reasonable time interval of \(\Delta T = \) one hour. Under this condition, each data retrieval from a meter can be done every \(n\) hours.

b. The Basic Operational Requirements.

The basic requirements are:

- Real time can be downloaded to the intelligent remote devices.
- The intelligent remote device reads the electric meter at specified time intervals and stores the meter reading data and times in its memory.
- The interval of time \(\Delta T\) is available for data retrieval from all the meters.

The ability to meet the above requirements depends greatly on the communication infrastructure and the operational design of the system.

**THE PHYSICAL PROPERTIES OF THE ELECTRIC POWER DISTRIBUTION NETWORK.**

a. Network Components

Most modern day electric distribution networks are designed to transport power at a frequency of 50 Hz or 60 Hz. The distribution network operates at a medium voltage which ranges between 4.0 kV to 34.5 kV. Medium voltage feeders emanate from a medium voltage bus to different parts of the service territory. Single phase or three phase taps are provided for transformers which step down the medium voltage to the service voltage. The transformers can be single phase or three phase and have ratings between 10 kVA to 2000 kVA. The service voltage network or sometimes called the low voltage network distributes the electric power directly to the users. Its operating voltage ranges from 100 V single phase to 480 V three phases. The medium voltage network and the low voltage network can consist of underground cables, overhead aerial lines or a mix of both types. Other components connected to the network are the capacitor banks, series or neutral reactors and not to be forgotten, the user appliances and electric equipment. These last few components can be switched in and out depending on the need and use. The actual network configuration has changed.

b. Network Configurations

The simplest configuration is the radial network as depicted in Fig. 2. Medium voltage feeders emanate from the medium voltage bus serving single phase or three phase distribution step down transformers. This configuration is very common in the USA, the distribution step-down transformers are usually single phase and connected line to neutral. The size of the transformers ranges from 10 kVA to 100 KVA. Each medium voltage feeder may have 50 to 100 of these transformers spread over all three phases. Many other countries use three phase step down transformers and the ratings are between 500 KVA to 2000 KVA. There are also a large number of electric users per transformer. To provide more flexibility and reliability of service, several feeders are sometimes interconnected to form a medium voltage network. These feeders derive their supplies from a single or multiple medium voltage buses. Fig. 3 shows a two feeder system interconnected at some intermediate segments to form a network. In this example the supply is from a single medium voltage bus. The same philosophy of interconnection is also often used at the low voltage network. Many metropolitan commercial and business areas are served by such a network and they are usually underground. The energy meters are clustered at the basements of the buildings.


The fundamental philosophy behind the design of the network is to transport electric power to every connected user in the most optimal and reliable fashion with minor voltage fluctuations. The idea that some day in the future the network might be used as a communication medium has never been considered. Several decades ago, telecommunication engineers have looked into the possibility to use the electric distribution
network as a communication medium. The main reason is that the electric distribution network reaches practically every residence, commercial and industrial building inside its service territory. If this proves successful, a tremendous amount of savings can be obtained for the cost of the communication infrastructure. Besides remote meter reading, the communication system can be used for other utility functions. Examples are load management, distribution automation, remote monitoring and alarms, etc.

Some insight can be gained about the propagation characteristics of a distribution network by measuring its transient oscillatory response due to a perturbation. (1) To stage such an experiment, a narrow current pulse of sufficient magnitude was drawn at the medium voltage bus. This current pulse simulates the perturbation function. The effect of the perturbation was then extracted from several remote locations at the network at the low voltage side of a step down transformer. One result obtained from a site which is approximately 65 km from the medium voltage bus is shown in Fig. 4. The response was a transient oscillatory wave and decayed to almost zero in less than half the period of the power voltage. Field studies also indicated that a small perturbation at a remote location has a response that can be detected at the medium voltage bus current. The transient response wave shape is similar to the one shown in Fig. 4. The transient oscillatory response (darkened part) is shown amplified by a factor of 500 in relation to the AC voltage wave. The transient oscillatory frequency is about 420 Hz. Subsequent measurements at different parts of the network served by the same medium voltage bus indicated fairly similar results of the transient response. It was also noticed that during certain period of the day, the frequency of the transient oscillation is much lower. Late at night, when the network load is small, the frequency tends to become higher. The lowering of the frequency of the transient oscillation can be attributed to the large number of capacitor banks connected to the network during heavy loading. The increase in frequency can also be attributed to the smaller number of capacitor banks in the circuit during periods of light load. The observed transient oscillations is the natural response of the network. This result gives us a clue what communication frequencies should be used for best signal propagation performance of the distribution network.

Another important consideration is the length of the medium voltage feeder. In some rural areas the feeders can be very long and closer to metropolitan areas they are of the order of a few kilometers only. If one assume that on aerial lines the electromagnetic wave propagation velocity is 300000 kilometer per second, then for the various carrier frequencies the length of a quarter wave can be calculated. TABLE I shows the results of such calculations. For medium feeder lengths of 7.5 km or longer, carrier frequencies of 10000 Hz or higher cause standing wave problems. For underground cables the quarter wavelengths for the various frequencies are even shorter. Dispersed branches or load taps also create different equivalent quarter wavelengths due to multiple reflections. Such a communication medium poses a very difficult problem for communication control. The problem stems from locations that are at or near a nodal point of a standing wave. The wave energy is almost zero at these locations.

Capacitance between different phase conductors can cause phase cross talk. A signal injected into a phase of the medium voltage feeder will appear on all three phases after a few kilometers. This is especially true for frequencies larger than 10 kHz. The strengths on the phases are not necessarily the same. Another important consideration is the capacitor bank for power factor correction and voltage control. They cause heavy signal attenuation at the higher frequencies. Underground cables also behave like capacitors and cause attenuation of high frequency signals. Transformers have transfer functions that are frequency dependent.(2) (3). At the power frequency and up to a certain harmonic level, the transformer can be modeled as a combination of resistance R and inductance L. At a higher frequencies, the inter winding and the capacitance to ground start to become significant. At much higher frequencies, the inductance L can practically be neglected.
Medium and high frequency signals from the low voltage network can easily spill over into another low voltage network. Power line technologies which use low frequency signals or carriers exhibit good propagation characteristics in the electric distribution network.

**TABLE I.**

<table>
<thead>
<tr>
<th>Carrier Frequency in Hz</th>
<th>Quarter wavelength in km</th>
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<tbody>
<tr>
<td>50</td>
<td>1500</td>
</tr>
<tr>
<td>60</td>
<td>1250</td>
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<tr>
<td>100</td>
<td>750</td>
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</tr>
<tr>
<td>125000</td>
<td>0.60</td>
</tr>
<tr>
<td>150000</td>
<td>0.50</td>
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The well known “Ripple Technology “ (4), the “Sequential Waveform Distortion (SWD)” (5) and the “Two-Way Automatic Communication System (TWACS)” (6), (7) have shown that the communication is not affected by the power network or network changes. The outbound transmitters for communication to the remote devices at the low voltage network are usually connected to the medium voltage bus. The TWACS and SWD technologies have the inbound transmitter at the remote devices and signals are sent back to the medium voltage substation bus and extracted from the bus current. The communication is very reliable and the achieved baud rate is low. However, for normal electric utility applications such as meter reading, load management and distribution automation, etc. they are adequate. Technologies which use higher frequencies (5 kHz to 15 kHz) require line conditioning of the medium voltage feeders. Wave traps, inductors at the power factor correction capacitor banks, etc. are required. Standing wave problems cause “blind spots”. Underground networks also pose problems due to signal or carrier attenuation.

Efforts to adapt technologies which are initially used for home automation are tried and used at the low voltage network for meter reading. The data concentrators are usually connected at the low voltage bus of the distribution transformer bus. The link to a Master Station computer is either telephone or RF. The frequencies used are larger than 15 kHz. The X-10 system, CEBUS compatible systems, etc. (8), (9) are some examples of commercially available systems. For step down transformers that are large and serve a large number of residences at the low voltage network they are viable. There are not too many of these large transformers per medium voltage bus and the number of links to the master station computer is also limited. This type of system is not too cost effective for use in systems with large numbers of small single phase step down transformers. Each transformer serves 5 to 10 residences and usually there are 20 to 50 of such transformers per radial medium voltage feeder. The number of data concentrators and links to the master station computer becomes extremely large. Some field investigations indicate that signal or carrier frequency spillover from the low voltage network to the medium voltage network does occur and penetrates through another step down transformer into the low voltage network. This may cause nuisance interference and collisions between two or more systems. Unfortunately these events are hard to predict and depend on load conditions and capacitor bank switching.

Numerous published studies have also shown that to make a communication link operate reliably between point to point on a segment of a medium voltage feeder is always possible. Heavy line conditioning, filtering, by-pass circuits and frequency adjustments are used. But this design is quite often not transportable to other parts of the electric network and massive changes and extensive measurements are required. For very large networks encompassing large service territories this is obviously impractical. Nothing is worse than having to treat many individual cases separately in a unique fashion. In addition, the electric network is really not static. Circuit expansion due to new area development causes network reconfiguration. Emergency switching and circuit segment transfer happen quite often.

**COMMUNICATION OPERATION DESIGN**

**a. Operational Requirements**

In the chapter on general operational issues, the need for hourly reading of the meter and time stamping the hourly data was discussed. The remote intelligent devices not only collect hourly data from the meter and save them in memory, but they also have to do accurate real time keeping. The communication from the central control computer to the remote devices is used to download meter reading activation commands and also to request the transmission of meter reading data. These transactions should be done within a specified time period \(\Delta T\) in order not to lose data. It is very likely that \(\Delta T\) is large enough to allow all electric meters to be read successfully. However there is one critical operation that does not have the luxury of time interval \(\Delta T\) at its disposal and that is the downloading of “real time” into the remote devices. Ideally speaking the real time information should be received by all remote devices at the same moment. The message length and communication delay introduce the inaccuracies. The degree of inaccuracy is a function of communication infrastructure design and communication control. Most power line communication systems which operate at the medium voltage level have the outbound transmitters connected to the bus of the medium voltage substation and operate in a master to slave mode. By using a global command the real time information is sent to all remote devices served by the medium voltage substation. For the whole electric utility each substation operates independently from the others. Hence all outbound
transmitters practically send the time information simultaneously in a parallel operation mode. The only skewing effect occurs because the transmitters have to access the feeder phases sequentially. There is no communication collision. Technologies which use medium frequency carrier suffer from a unique problem. The blind spots due to standing wave problems cause uncertainties about whether real time clock information have been received by all remote units.

Technologies which operates at the low voltage network designed for home automation are usually designed for master to master or peer to peer operation. CSMA and CDMA are natural requirements of this system to overcome collision problems and to allow for retreat and retry when there is a contention. For these types of systems, peer to peer communications by many remote units cause random time delays of receiving the real time information by each remote device. The real time skew amongst individual units will depend on the number of devices per low voltage network, the length of message and the number of communication retries. The possibility of spill over from other low voltage networks at the other transformers connected to the same medium voltage feeder, adds to the time delay problem.

There is also a need to send new time information at specific intervals of time. Outages do occur and care has to be taken that this operation is not in collision with the communication activities during retrieval of all meter readings.

CONCLUSIONS

Low frequency communication at frequencies of 1 KHz or below at a utility network gives the best propagation performance. In general this communication system is considered slow. But for electric utility applications it is adequate. Reading quite a few thousand meters per hour per network served by one medium voltage substation is possible. For \( N \) such substations per electric utility the total metering data throughput per hour is \( N \) times larger. Networks at the low voltage network or at the medium voltage circuit as shown in Fig. 3 might pose a problem if the network is served by multiple medium voltage sources. Data concentrators are needed only at the medium voltage substations. Since the system is normally designed to operate in a master-slave relationship between one outbound transmitter and all the remote devices, real time downloading to the remote devices cause minimal time skew amongst the remote devices. The higher frequency systems might operate well if line conditioning and bypass devices are used and some solution can be provided to eliminate the effects of standing waves.

High frequency PLC at the low voltage network can be economical at systems with large low voltage networks and not too many step down transformers. For systems with large number of step down transformers per feeder, too many data concentrators are required. Peer to peer operation causes delay in downloading of real time clock information.

REFERENCES