OPTICAL COMMUNICATIONS TO THE HOME WITH ELECTRIC POWER?

by Egill B. Hreinsson

I. INTRODUCTION

Optical fibers as a communication medium have been projected to reach increasingly into the home in the near future for providing telephone, video, and computer communication services to individual homes/business for the much heralded information age of tomorrow. This requires optical fiber cables to be laid to each home replacing today’s telephone cables with twisted copper wires and laid in somewhat similar manner as electrical distribution cables for providing electricity. Historically, of course, it has not been possible to combine electric power and telephone in one hybrid cable due to interference problems. Optical fibers and electric power can however be combined in such a cable, since light, as well known, is not disturbed by electricity.

This paper addresses the issue whether it might be technically feasible and economically beneficial to combine the distribution of telecommunications and electricity to share almost unlimited bandwidth (and costs) and transmission capacity of fibers and satisfy the telecommunication need’s of the electric power industry.

Numerous new services can be offered through the future broadband network. Distributive video, on demand video, POTS (plain old telephone service), computer communications, alarms, telemarketing, electronic banking etc, are examples. Generally, however the only service which is known to generate considerable revenue besides POTS, is the distribution of entertainment video. This distribution is however generally provided by Cable Television (CATV) companies.

Many studies have been done from the perspective of Public Telephone Authorities (PTA’s) or Local Exchange Carriers (LEC’s) and CATV companies of the future broadband network. Separate studies have as well been done on the viability of optical communications within the power system. This paper addresses both perspectives on an equality basis. Although the traditional distribution automation (DA) needs may not be classified as “broad band”, optical fibers have been a very important subject of study, mainly due to their inherent immunity to electrical interference and large transmission bandwidth. Hence, huge extra transmission capacity is available to share, but institutional barriers have often prevented EDU’s from working with PTA/LEC’s.

It is therefore, again, a logical question whether or not the 3 domains (telephone, TV, electric power) if working together to form a single broadband network, instead of 3 separate fiber optic networks, would not be in a stronger position to break the dilemma and establish a broadband network which would be supported by revenue and savings from comprehensive services in the three domains, perhaps with the addition to various computer communication related services. A technical factor supporting this argument is the similarity in the distribution hierarchy of the systems down from a central facility to the multitude of customers.

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In this paper we will first examine the structure of the electrical and telecommunication distribution systems, then look at possibilities for combination, assuming a Scandinavia/European type of electrical distribution system. Finally a case study is presented where hybrid electrical/optical cables are compared against traditional separate cabling.

II. THE STRUCTURE OF ELECTRICAL POWER DISTRIBUTION

Today’s electrical 3-phase distribution system is constructed in a hierarchical manner, conceptually shown in fig 1. The system is usually operated in a radial manner, i.e. without inner loops, although different radial configurations are possible through switching. The transport of electrical power downward, perhaps from a single entry point, through the expanding hierarchy to the multitude of customers is facilitated by the proper selection of voltage and conductor sizes.

In systems similar to those in Scandinavia and Germany, the system is in urban or suburban areas almost totally underground with buried cables. Also the above levels of the hierarchy and the “splitting points” are fairly standard. As seen in fig 1 between the entry point and the customers are three levels of the hierarchy, that is (1) substations, (2) distribution stations and (3) street cubicles. An extra splitting level is introduced since more than one customer (electricity meter) is connected to each home feeder. We will briefly examine each level.

The substations transform the power from a subtransmission voltage (60 kV to 380 kV) to a feeder voltage (6 kV to 60 kV). Although the number of substations varies somewhat depending on the specific system, there are approximately 5000 to 15000 inhabitants for each substation. From the substation, power is supplied to the distribution stations through an arrangement consisting of a mixture of star and bus configuration. Figures 2 and 3 show a generic arrangement in detail.

The distribution stations contain 3 phase electrical transformers, which convert high voltage (6-30 kV) to low voltage (400 volts). The power is fed from the stations through underground three phase cables to the street cubicles which distribute it to the individual homes or businesses. Beside transformers, the distribution stations usually contain disconnect switches on the high voltage side and circuit breakers on the low voltage side in addition to various metering and protecting apparatus. In Scandinavia the urban distribution stations are usually indoor units, housed in prefabricated houses.

Figure 4 shows a distribution station which usually has 11 kV high voltage side and 6 outlets (400 volts). The low voltage cables to the street cubicles are 3 phase 4 wire aluminum conductor direct burial cables of 4 ×150 mm² or 4 × 95 mm² thickness, where the 4th conductor is connected to the neutral of the 3 phase system.

Street cubicles usually directly connect to each individual customer or meter, one per household or small business. From the street cubicles a separate cable usually runs to each household - for instance 4 × 10 mm² with copper conductors. In some cases the house owner is required to supply a tube (perhaps 50 mm in diameter) to the limits of his lot: The EDU can then pull the cables through the tubes. (Similar tubes are sometimes supplied for telephone cables). The average length of the low voltage home feeders in the order of 20-60 m and usually there are approximately 2-8 houses connected to each street cubicle. Typical number of street cubicles per outlet from a distribution station is 3-8 and the distance between linked cubicles is in the order of 100 m.
III. AUTOMATION IN ELECTRICAL POWER DISTRIBUTION

An electric power system can be defined to include a generation, a transmission and a distribution system. In broad terms it is often stated that the total investments in the distribution system equal those in the generation system. Nevertheless, the reality is that the distribution system has not been the beneficiary of the careful engineering, planning or design that characterize the generation system. In particular, the use of automation, telecommunications and computers is generally far more sophisticated in the generation and transmission part than the distribution part of the electric power system. Today, the situation is gradually changing and the use of telecommunications to move information and data is continually increasing, not the least in the distribution part of the system.

In the past, the electrical distribution system generally only been covered down to include the substation level in the hierarchy (see fig 1) with information technology equipment. We will here review distribution automation (DA). Although no standard definition exists for the term, “distribution automation” is generally taken to include the remote and automatic control of functions required by electric power utilities for the operation of their distribution system. We will here examine some of the salient features of DA.

Listed below are some of the main functions associated with Distribution Automation (DA):

- Monitoring of the performance and the equipment of the power system, (such as transformer temperature reading)
- Remote reading of customers meters
- Detection of unauthorized energy use
- Control of voltage in the power system
- Detection of outages and their location
- Reconfiguration of the system following a fault, (such as distribution feeder switching)
- Balancing of loads for optimal system operation
- Collecting load data for system planning
- Provide new relay protection functions
- Provide new services or tariffs to attract new customers such as “time of day metering”
- Management of customers loads (such as to reduce electric power demand during critical load periods or furnish a demand monitor for key customers or customer groups)

Although these are the major functions generally associated with DA, there are more, and such lists as shown above can be considered a “wish-list”, where a system utilizing only a fraction of the above list can still be considered a DA-system. The objectives with distribution automation could be summarized by factors such as:

- Reduce power generation, energy purchasing or supply requirements
- Cut down utility’s investment and operating costs
- Ensure acceptable system reliability and quality of service
- Ensure acceptable low level of customer inconvenience
- Maintain an acceptable cost benefit ratio for the system
Despite these very important objectives, utilities have to a limited extent found it feasible to implement DA in their distribution systems to the degree usually found in their generation and transmission part. One difficulty with DA lies in the disperse nature of the distribution system as compared with the generation and transmission system. There are hundreds of more points to monitor each handling perhaps only a few kilowatts. This brings the economics in terms of dollars per customer or dollars per point in the unfavorable range. The problem is that many utilities have in many cases been sufficiently protected by the regulatory environment so they do not have to run even the slightest financial risk.

Another problem with distribution automation has been the lack of economic communications. Many communication media have been proposed, tested and used. The main problem has probably however been the cost of communications, which has hitherto been far too high so that DA functions could alone economically justify an investment in a comprehensive communication system within the distribution system. Many utilities are relying on older technologies, such as copper or coaxial cables, which could nicely do the job with the rather limited communication speeds required for DA. Power Line Carrier (PLC) or VHF radio is being offered by vendors or the use of the customer telephones.

However, none of the above technologies are forward looking, both limited in data rate and subject to interference. Optical fibers is however a technology which does not suffer from these important drawbacks. In the near future the EDU’s are going to be faced with 3 choices, (1) do nothing and continue to operate the system with poor knowledge of what is actually happening, (2) do a limited amount of DA using old technologies or (3) or use some wideband system for fully fledged Distribution Automation. If they choose the last of these 3 there is practically no alternative to using optical fibers and therefore there is probably a general consensus today that optical fibers - of the different communication media - are best suited for the future implementation of DA when the time is ripe for such a serious development.

IV. COMMUNICATION REQUIREMENTS FOR AUTOMATION

The communication requirements for DA will in principle depend on which functions are to be implemented in each particular projects, but in general the rates are quite modest. Typical figures arrived at when examining the number of points (breaker, meters, capacitors, etc) at each high voltage feeder or customer point, and assuming a certain scan rate (poll rate) from the RTU (Remote Terminal Unit) are in the order of perhaps 1000-5000 bits/sec/feeder. With each feeder supplied with fiber optic communication channels, the above rate is certainly modest compared to the capacity of the medium.

The above low information rates are basically an invitation to the idea of sharing this medium with other telecommunication applications such as telephones, television etc., considering the vast capacity of the optical fibers medium.

Looking at economics of DA, Remote meter reading is a case where benefits from DA can be easily measured. Utilities have traditionally read the kWh energy meters by dispatching special crews to go from house to house (meter to meter) and logging by hand the current reading. We will present an estimated benefit of automatic meter reading for the Reykjavik Municipal Utility (RR), Iceland which at a price level in mid-1991 is approximately $2.50/reading. This includes labor costs for
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meter reading crews, transportation costs and cost of converting the information to a computer readable form. Assuming 10% interest rate, this corresponds, in terms of present worth, to $50-$150 per customer assuming 2 or more remote readings per year, or if expanded for the whole RR system with about 70,000 customers to about 3.5 - 10.5 Million U.S. $.

V. TELECOMMUNICATIONS DISTRIBUTION TODAY AND TOMORROW

The present distribution of telecommunication, with particular reference to conditions in Iceland and Scandinavia basically consist of:

1. Plain Old Telephone Service (POTS)
2. Video and Television Distribution

Plain Old Telephone Service (POTS) involves ordinary telephone service as we know it. It involves locating a number of central offices (CO) in the area and connecting subscribers individually to the CO’s by underground “twisted copper wires” with an architecture, which could be termed “Single Star”, see figure 5. Between the subscriber and the CO, are “connection boxes” (CB’s), metallic cabinets, similar to the street cubicles as previously described. Both these devices are connection devices to connect to the customer. Although similar, the 2 systems have evolved independently from each other.

Many “Fibers-to-the-home” systems have been proposed and perhaps hundreds of experimental systems exist around the world with experimental broadband service. Some of the architectures proposed are (1) The Single Star (2) Active Double Star (3) Passive Double Star (4) Bus. Common to these architectures is the feature of a single route to customer.

The Single Star networks are similar to the existing voice network (POTS) dedicating individual fiber from the CO to each subscriber. All switching occurs at the CO. The principal disadvantage with this architecture is the amount of fiber required, but it is preferred when the cost of switching is very high relative to the cost of transmission capacity. The Single Star is conceptually shown in fig 6.

The Active Double Star architecture differs from the Single Star in that Remote Distribution Units (RDU) are deployed at selected location. This introduces “fiber gain” over the feeder fiber from the CO and a certain amount of fiber can be removed as shown in fig 6(lower part). The Passive Double Star approach is similar to the Active Double Star, except that the RDU is equipped with passive rather than active devices. At the CO the downstream signal is multiplexed with TDM (Time Division Multiplexing) or WDM (Wavelength Division Multiplexing) onto a single fiber. At the RDU a passive splitter replicates the optical signal onto individual distribution fibers and finally the equipment at the subscribers premises selects the correct signal from the several multiplexed on the fiber using information sent from the CO. Having the signal of several subscribers come into each household, raises the issue of securing the information privacy of each subscriber.

The principal cost lies in the fiber and splicing and multiplexing and terminating equipment, which are the trade-off factor to be considered, when combining the 2 networks.
VI. INTEGRATED DISTRIBUTION OF ELECTRICAL POWER AND TELECOMMUNICATIONS

The broadband information network of the future - whether integrated with electric power or not - will have the capabilities of offering a multitude of new information services, such as:

1. POTS (= plain old telephone service).
2. Information monitoring and control services, such as remotely monitor security systems, home and building management systems, remote medical diagnosis and examination etc.
3. Video teleconferencing. In spite of the failure of the video-phones of the 60’s and 70’s, this technology might make a comeback!
4. Multimedia teleconferencing. This is essentially a teleconference with video, voice, hardcopy (telefax), graphics, electronic file transfer etc.
5. Distributive video. This is the traditional cable TV distributing a specified number of “TV-channels”.
6. On-demand video. The subscriber requests a certain TV-program (such as a movie) a time specified by him and convenient for him.
7. Database and information services where the user can access a database from his terminal.
8. Telemarketing services. This includes video catalogue shopping both business-residence and business-business.
9. Continuing remote education. This involves the possibility to connect to students in their home through one-way video or two-way video-audio on an individual basis.

The above list is traditional in the sense that it does not include communication “services” by the electric utility. By adding to the list some of the functions of distribution automation, we get the following additional items:

11. Spot pricing of electricity.
12. Load management and control.

The principal services being able with certainty to generate revenue today are POTS, remote meter reading and video distribution. The quantitative benefits of other services are today more or less uncertain or intangible.

An important question concerning Integrated Distribution is whether hybrid electrical optical cables would introduce cost savings relative to separate cables. The following important questions will now be addressed:

1. Is it cheaper to manufacture a single hybrid cable than 2 separate cables?
2. Is it cheaper to lay a single hybrid cable than 2 separate cables?

It is well known that an important cost factor of an underground distribution system, whether for electricity or telecommunication, is the cost of digging trenches for cables. It is therefore natural to try to save on this cost, for instance by using the same trench for as many cables as possible.
Therefore, the incremental installation (labor) cost of adding a telecommunication cable (fiber or copper) to a trench with an electrical cable is much less than the installation cost of a single cable, since in most cases only a single trench will be needed. However, there are certain installation costs associated with the extra cable, which in our assessment amount to approximately 20% of the installation cost of a single cable. These cost factors include (a) The labor cost of laying a “thin” cable in an open trench. This cost is estimated to be 0.20 - 0.30 U.S. $/m. (b) The cost associated with cable crew synchronization and cost of waiting for such crews. (c) The overhead costs of extra facilities associated with cable laying as compared to the facilities needed for hybrid cables.

Several additional issues affect the feasibility of using hybrid cables. An advantage of using hybrid cables in electrical power systems is the possibility to monitor short circuits and do thermal measurements, find “hot spots” and develop temperature profiles along the length of the cable by using the fiber as optical transducers. However, hybrid cables demand different skills for terminating and connecting (splicing) both the electrical and the optical part where alongside the fibers are conductors with lethal potential. This raises craft issues, which today are not solved. These different skills are undoubtedly a disadvantage today, although combining the termination skills for high voltage connections and fiber splicing could probably easily be coordinated in the same person.

Therefore the cost of laying two separate cables does not seem significantly higher than the cost of laying a single hybrid cable. Although the handling and even laying cost is implicitly lower for a single cable the quantified benefits seem rather marginal. Advantages of two separate cables include increased flexibility regarding splicing and routing.

VII. INTEGRATED DISTRIBUTION IN AN ICELAND/SCANDINAVIAN PERSPECTIVE. A CASE STUDY

Finally we will examine quantitatively the alternatives of a single hybrid electrical/optical cable versus separate cables. Network data from Reykjavik Electrical Municipal Works (RR) form a basis for calculations. A simple spreadsheet model (fig 7) describing the distribution network of the RR system is used and there, the extra splicing and manufacturing costs of hybrid cables is compared to the savings involved in installing a single cable.

The model assumes the following relations between adjacent levels in the distribution hierarchy.

- 10 Substations.
- 15 High Voltage feeders (HV) for each substation.
- 5 distribution stations for each HV feeder.
- Low voltage (LV) feeders for each distribution station.
- 3 Street cubicles for each LV feeder.
- 3 Home feeders for each street cubicle.
- 2 subscribers for each home feeder.
- HV feeder average length: 3000 m.
- LV feeder average length 300 m.
- Home feeder average length: 30 m.
Fig 7 shows some actual data for comparison. We assume fibers are installed in both the HV and LV cables. The extra splicing and manufacturing costs of hybrid cables is weighted in this model against the savings involved in installing a single cable vs. two separate cables. The following comments apply to the cost model and the study:

1. Using information from manufacturers, cable manufacturing costs are estimated higher for a single hybrid cable than separate optical cable using the same number of fibers. The difference is assumed $4.00 per meter between the two types of cable. Using the implicit assumption that the cost per fiber meter for additional fibers in both types of cable is the same, gives the estimate of cost differences as shown in fig 7. For example the manufacturing cost of fibers in a 450 km HV feeder network is $4.00 \times 450 \times 1000$ or $1.800.000$ higher for a hybrid cable than an optical one. (See Column 2, fig 7).

2. Installing a single hybrid cable is cheaper since in essence the workload has been reduced by installing one cable instead of two. For instance, in figure 7, these savings for a HV feeder are assumed $5.00 per meter which results in total savings of $2.250.000 since the total length of these feeders is 450 km. The figure of $5.00 per meter equals 20% of the unit labor cost ($25 per meter) of installing these HV feeders and the 20% figure reflects an assessment of additional installation costs for two separate cables versus a single hybrid cable.

3. With the “Passive RDU WDM fiber gain” equal to 1 we assume a single star architecture, while if this factor is greater than 1 it assumes double star architecture. From the table costs and savings can be estimated in the HV and LV part of the system assuming a CO located at a substation or equivalent location. The CO has to be co-located with a critical splitting point in the electrical system - such as a distribution substation - assuming coordinated planning from the start.

4. The distribution station is chosen as the candidate location for a passive RDU. Approximately 100 subscribers are for each distribution station.

5. The number of fibers in a single LV feeder is shown in figure 8 with 3 street cubicles and 3 home feeders per cubicle. The average number of fibers per cable and splices per cubicle is 6. Similarly the average number of fibers and splices in a HV feeder is shown in figure 9. Splicing costs are assumed 20 U.S. $/m with fusion splicing.

6. It can be concluded from the study that the use of hybrid electrical/optical is marginally more expensive than using separate cables and therefore there is presently no direct economic incentive to use hybrid cables. Naturally, if technology and manufacturing costs will change in the future with the reduction of the cost of making hybrid cables this result may change in favor for hybrid cables. Cable manufacturers should be addressing this issue, which at present is uncertain.

7. The study has however shown that using hybrid cables may not be a critical issue regarding the benefits of cooperation between electrical utilities and telephone companies. By working closely together and sharing the cost and bandwidth of a high capacity broadband fiber-optic network (whether with hybrid cables or not) new services could be offered and e.g. joint ventures in this field could accelerate the development of this network.

VIII. REFERENCES AND BIBLIOGRAPHY


Figure 1

Schematic Electrical Distribution Hierarchy
Figure 2

A generic geographical layout in urban low voltage distribution
Figure 3
A Generic Electricity Distribution System
Figure 4

A typical arrangement in a distribution station
Figure 5
The architecture of present telephone service distribution
The single star or switched star architecture.

Double star architecture
Cost comparison - hybrid vs. separate cables for RR system

A) Assumptions and systems characteristics

<table>
<thead>
<tr>
<th>Splicing costs (U.S.$/splice)</th>
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<td>Hybrid cable incremental manuf. cost, first fiber (U.S.$/fiber meter)</td>
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<td>Hybrid cable incremental installation cost saving factor (%)</td>
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<td>Passive KDU WDM fiber gain</td>
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<table>
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<th>Hierarchy level: Number</th>
<th>Substation</th>
<th>LV feeder</th>
<th>Distrib. station</th>
<th>LV feeder</th>
<th>Street cubicles</th>
<th>Home feeder</th>
<th>System (subscribers)</th>
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<td>Street cubicles</td>
<td>Home feeder</td>
<td>System (subscribers)</td>
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<td>5</td>
<td>5</td>
<td>3</td>
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<td>Total number at each level (model)</td>
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<td>150</td>
<td>750</td>
<td>3,750</td>
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B) Cable installation costs

Average installation costs:
- Unit cost, materials (U.S.$/m) | 20 |
- Unit cost, labor (U.S.$/m) | 15 |
- Total unit cost (U.S.$/m) | 35 |
- Total cable installation cost (U.S.$) | 20,250,000 |

Installation cost per subscriber (U.S.$):
- Installation cost per subscriber (average) | 300 |
- Installation cost per subscriber (%) | 27.1% |

C) Cost differences of hybrid vs. separate cables

Fiber (Average amount per cable) | 15 |
Incremental hybrid cable material cost (U.S.$) | 1,800,000 |
Splicings per subscriber (number) | 100 |
Splicings per subscriber (cost) | 10,000 |
Incremental hybrid cable splicing costs (U.S.$) | 2,025,000 |
Cost savings by hybrid installation (U.S.$/m) | 5.00 |
Cost savings by hybrid installation (U.S.$) | 2,250,000 |
Net hybrid cable installation cost | -450,000 |
Net hybrid cost per subscriber | 74 |

Figure 7
Figure 8

Fiber splicing and count in a LV feeder.
Figure 9
Fiber splicing and count in a HV feeder.