Transmission Capacity Estimation for the Medium Voltage Level of Smart Grid

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Abstract. *It is clear that communication infrastructure will must be gradually extended to lower levels of energy grid, primary to medium and low-voltage levels. The information capacity of the backhaul part of the communication network will be continuously increased as a result of Smart Grid services expanding. In this paper, the data rate analysis of the backhaul links on medium-voltage power grid level is presented. The network model and calculation of aggregate data rate method for the medium-voltage section is designed. In next part, the experimental results of broadband power line communication are presented and these results are compared with aggregated data transmission requirements. Usability of broadband power line communication is discussed and gradual transition to optic fibre communications is predicted.*

Keywords

Broadband power line communication, communication networks, Smart Grid, transmission capacity.

1. Introduction

Today, the public and private telecommunication networks can be generally characterized by the increasing demands for transmission capacities and the subsequent preference of optical fibres. There are still some specific environments and applications that seek for utilization of the existing metallic lines, for example power lines in energy grid.

The concept of Smart Grids in power distribution systems implies the need for data transmission on all levels of distribution power grid from backbone level on High-Voltage (HV) to access level on Low-Voltage (LV). The communication over Medium-Voltage (MV) lines can be used on the middle level for data connection (backhaul level) of the distribution transformation stations. Primarily, the Broadband Power Line (BPL) communication systems in frequency bands from 2 to 12 or 30 MHz are used on MV lines.

Therefore, it is necessary to solve some specific problems related to this environment (for example impedance inhomogeneities, impulse noise, coupling circuits), sometimes substantially different from the issues known in conventional telecommunication lines and cables [5], [6], [7] and [8].

Generally, the role of ICT technologies in the Smart Grids concept, especially from the viewpoint of the required data rates, quality of service, availability and reliability, is explained in many articles, for example [1]. Transmission capacity and other transmission parameters are closely linked to the Quality of Service (QoS), as described by [3] and [4] for common telecommunication networks.

In this paper, the data rate analysis of the backhaul connection on Medium-Voltage level between backbone network (High-Voltage level) and access network (Low-Voltage level) is presented. The network model and calculation of aggregate data rate method for the Medium-Voltage section is designed. In next part, the experimental results of BPL communication are presented and these results are compared with aggregated data transmission requirements. Finally, usability of broadband power line communication is discussed and gradual transition to optic fibre communications is predicted.

2. Networks Levels and Topology

2.1. Network Levels in Smart Grid

The Smart Grid consist from three basic components based on SGRIM (Smart Grid Reference Interoperability Model) [11]:

- Energy plane.
- Information plane.
- Communication plane.

The communication levels of Smart Grid can be divided as follows:

- Backbone network:
  - 1-HV-WAN - the core WAN network connects central systems (eg. SCADA) and main HV stations.
  - 2-HV-WAN - the regional WAN network connects other HV stations.
- Backhaul network:
  - 3-MV-WAN - the regional WAN network connects MV stations.
  - 4-MV-MAN - the MAN network connects metropolitan MV stations (can be divided to two levels - switching and transformation stations - in the main cities).
- Access network:
  - 5-LV-WAN - the regional WAN or MAN network (typically radio network) connects subscribers to Smart Grid.
  - 6-LV-MAN - the MAN network connects subscribers to Smart Grid (can be divided to two levels - switching level and end user level - in the main cities).

This paper is primary focused on backhaul level and network nodes in the medium voltage stations.

2.2. Network Topology

The network design processing is based on the methodology mentioned in [2] for LTE backhaul. The same methodology can be used for Smart Grid MV backhaul. The simplified network layout is shown in Fig. 1.

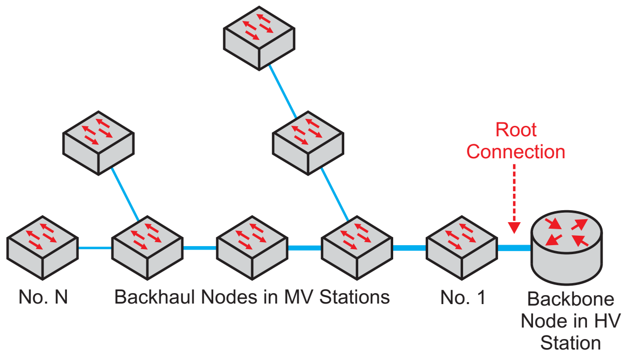

Fig. 1: Typical tree topology of the backhaul MV network (data aggregation indicated by an amplifying blue line; maximum data rate in root connection at backbone node).

In the elementary model case, the backhaul network of MV station is created by successive cascade connections, so streams are merged (aggregated - indicated by an amplifying blue line) to the root connection that the topological tree connects to the backbone node.

The topological tree can have various number of MV stations (generally N), where $N = 1$ represents an MV station individually connected to the backbone network. It is clear that increasing N will also increase requirements for intermediate links and in particular for the root link of the backhaul network.

3. Calculation of Aggregated Transmission Capacity

3.1. Input Parameters

Primarily, all types of data streams for communication services must be described for network design. Types of Smart Grid services can be divided as follows:

- MV station control:
  - State information.
  - Periodical data from quality meter (today typically with period 10 minutes).
  - Technology and security monitoring.
  - Ad-hoc control, switching and regulation.
- AMM (Automated Meter Management):
  - State information.
  - Periodical data from Smart Meters (today typically with period 15 minutes).
  - Ad-hoc measurement.
  - Load control based on TOU (Time of Use) tables.
  - Ad-hoc load control.

- MV line protection and real-time processing:
  - Differential measurement on end-points of protected line.
  - WAMS - Wide Area Monitoring System.
  - WAMPAC - Wide Area Monitoring, Protection and Control System.

At the same time, sites with different traffic intensities will be considered:

- Locations with station control only.
- Locations with station control and AMM (data from concentrators on LV level).
- Locations with station control, AMM and MV line protection.

The purpose of the data rate calculation is to estimate the transmission link capacity depending on:

- The number of MV stations in a topological tree.
- The number of MV station sectors.
- The number and types of Smart Grid Services.
- The type of traffic intensity.
- The timeframe depends on the increase of the number of Smart Grid services and the increase of network load with the traffic increase.
- The transmission direction - primarily calculated for the uplink direction (higher data rates from stations to central systems for main types of services).

The basic input data were:

- Mean Rate MR_{ij} per section and services (or total speed at MV station MR_{sj}).
- Peak Rate per per section and services (or total peak speed at MV station PR_{sj}).

3.2. Calculation Procedure

By partial calculations, the following parameters can be obtained.

The Total Mean Rate per MV station for "S" Station Sectors and all "L" Smart Grid Services:

$$MR_{sj} = S \cdot \sum_{i}^{L} MR_{ij}. \tag{1}$$

The Peak Rate per the MV station:

$$PR_{sj} = MR_{sj} + \max_i(PR_{ij}). \tag{2}$$

The Total Mean Rate per MV station calculated with various conditions in energy distribution regions as arithmetic mean calculation, P is the number of types of regions:

$$MR_s = \frac{1}{p} \cdot \sum_{j}^{P} MR_{sj}. \tag{3}$$

The Peak Rate per the MV station calculated with the data of all P types of regions by selecting the maximum from partial peak rates:

$$PR_s = \max_{j=1\ldots P}(PR_{sj}). \tag{4}$$

The Corrected Mean Rate per the MV station calculated with the reserve for overhead and service communications R ($R = 1$ corresponding to the 100 % increase of data rate):

$$MR_{sc} = MR_s \cdot (1 + R). \tag{5}$$

The Corrected Peak Rate per the MV station calculated with the reserve for service communications R ($R = 1$ corresponding to the 100 % increase of data rate):

$$PR_{sc} = PR_s \cdot (1 + R). \tag{6}$$

The final calculation can be made as combination of N aggregated data streams with mean rate and maximum of peak rates.

3.3. Data Stream Aggregation for BPL MV Segment

The final calculation shows the dependence of the required transfer rate of the root link on the number of MV stations N in the topological tree, which respects the need to serve both the peak of the operation and the steady aggregate flows during the period of strong operation:

$$SR = \max(N \cdot MR_{sc};\ PR_{sc}). \tag{7}$$

Calculated transition rates are shown in graph (Fig. 2) based on the number of MV stations according to the different traffic intensity (A, B, C) and time horizon (periods 1, 2, 3). Obviously, the 1 Mb$\cdot$s^{-1} speed limit will be exceed around the year 2020, the 10 Mb$\cdot$s^{-1} speed limit will be exceed by 2030 and the 100 Mb$\cdot$s^{-1} speed limit will be exceed by the year 2040.

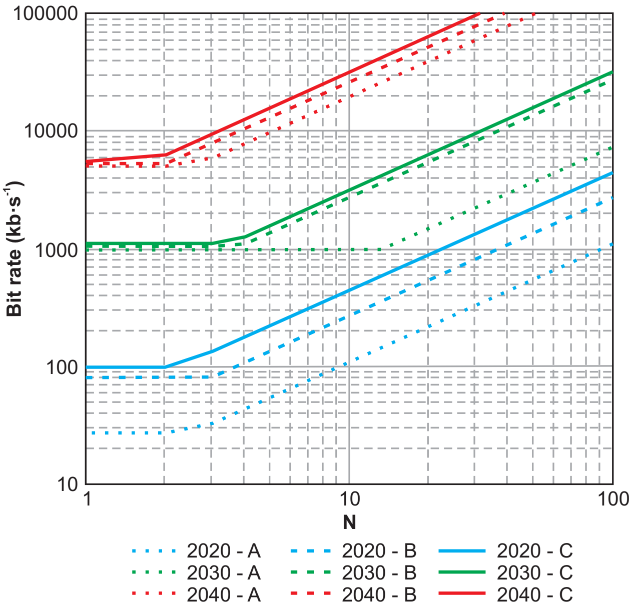

Fig. 2: Data aggregation of transmission from multiple MV power stations for different traffic intensity (A, B, C) and time horizons (2020, 2030, 2040).

4. Transmission Capacity of One BPL Section

4.1. MV Communication

Medium-Voltage power distribution network has, in general, a tree topology with many branches (that we refer to as bridged taps, with respect to the common terminology used in the telecommunications area [7]). For the purposes of modelling of the medium-voltage transmission environment for PLC communication, we will consider three basic topological configurations:

- Tree topology.
- Linear topology with very short taps.
- Star topology.

However, the point-to-point (P2P) topology between neighbouring MV stations can be assumed for cable MV lines.

In any case, two types of coupling can be used for signal injection to the power lines:

- Capacitive coupling directly to phase line (on overhead and cable MV lines).
- Inductive coupling to the cable shielding (on cable MV lines only).

4.2. Transmission Capacity of BPL Section

Basically, the transmission function of the line and noise in receiver input determine the signal-to-noise ratio, and subsequently, together with the system bandwidth, transmission capacity of a communication channel.

The experimental results of BPL communication bit rates were used in this paper. The presented selection of measurement results on the real power line MV grid shows the importance of complex stress testing and evaluation methodology [9] and [10].

The measured results on metropolitan MV cable lines with P2P topology and capacitive coupling were processed into a simple distance dependence model. The bit rate BR on the physical layer in Mb·s^{-1} can by calculated as:

$$BR = BR_0 \cdot e^{-k \cdot d}, \qquad (8)$$

where BR_0 is the parameter of the model, k is the slope coefficient and d is the distance in km. The distance dependence with $BR_0 = 54$ and $k = 1$ is shown in graph (Fig. 3).

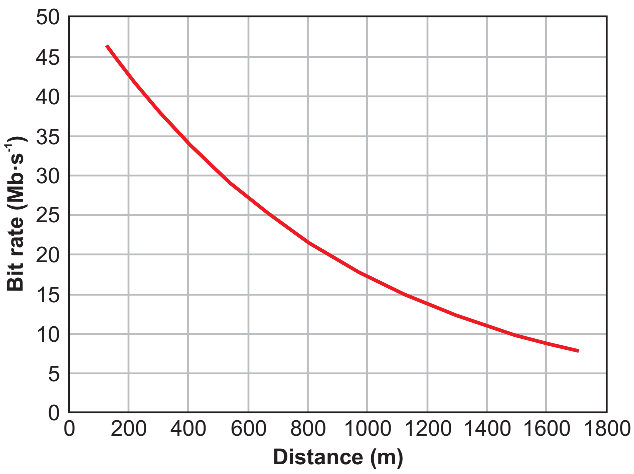

Fig. 3: Bit rate distance dependence for one P2P MV section for BPL communication with capacitive coupling.

The usable transmission capacity for asymmetrical TCP/IP communication is approximately a half of values in graph (after subtraction of headers and overhead during time division duplex method).

4.3. Comparison Transmission Capacity and Data Rate Requirements

Based on the comparison of values from Fig. 2 (aggregated data rates of MV stations) and Fig. 3 (transmission capacity of BPL section), the results can be summarized as follows:

- The BPL communication can be used in first time horizon (2020) on MV sections without limits to maximum distance (approx. 1.8 km).
- The BPL communication can be used in second time horizon (2030) on MV root sections with $N = 20$ MV stations to maximum distance about 1 km.
- The BPL communication can be used in third time horizon (2040) on MV sections with a low number of stations for a short distance (for example: $N = 5$; root distance about 300 m).

Prospectively, the cables with optic fibers must be installed at overhead MV line and ground MV cables (typically as added optic cable during power cable reconstructions).

5. Conclusion

In this paper, the data rate analysis of the backhaul connection on Medium-Voltage level between backbone network (High-Voltage level) and access network (Low-Voltage level) was presented. The network model and calculation of aggregate data rate method for the medium-voltage section was designed.

Finally, the implementation of the backhaul communication network for medium-voltage Smart Grid using optical fibres is undoubtedly the most prospective one. Its advantages of optical fibres are high reliability and very low bit error rate, practically unlimited transmission capacity and longest possible communication distance. Common current transmission rates are from 1 to 100 $\text{Gb}\cdot\text{s}^{-1}$. With the wave division multiplex, the current optical communication systems have a 120 km bridging range and a rate of 2 $\text{Tb}\cdot\text{s}^{-1}$. Future communication systems will provide a 180 km bridging range and a theoretical rate of 96 $\text{Tb}\cdot\text{s}^{-1}$.

However, the Broadband Power Line (BPL) communication will be used by 2030 still on medium-voltage root sections with $N = 20$ medium-voltage stations to maximum distance about 1 km. In next period, the BPL communication will be moved to the marginal parts of backhaul medium-voltage networks.

In the last sections of the backhaul network, where optical infrastructure is not economically efficient, BPL links will still be used to ensure communication up to 10 $\text{Mb}\cdot\text{s}^{-1}$.

Another expected trend in point-to-point BPL links is the application of Multiple-Input Multiple-Output (MIMO) techniques on three phases of power line. With multi-coupling system, multiple parallel transceivers and adaptive interference suppression, typically triple (MIMO 3×3) transmission rates can be achieved compared with classic BPL links (SISO - Single-Input Single-Output).

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Jiri VODRAZKA was born in Prague, Czech Republic in 1966. He joined the Department of Telecommunication Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague in 1996 as a research assistant and received his Ph.D. degree in electrical engineering in 2001. He has been the head of the Transmission Media and Systems scientific group since 2005 and became Associate Professor in 2008. He participates in numerous projects in cooperation with external bodies. Currently he acts also as vice-head of the Department.