Czech Technical University in Prague
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Modeling of optical communication infrastructure building for energy distribution network operator

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Declaration

I declare that the thesis is my original work and it has been developed with the contribution of my supervisor. Only the sources cited have been used in the thesis. Parts that are direct quotes or paraphrases are identified as such. I further declare that I have no objection to the loan or publication of my thesis or any part of it with the permission of the department.

In Prague, 19.05.2022 ....

Student's signature

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Modelování výstavby optické komunikační infrastruktury pro potřeby provozovatele distribuční sítě

Název diplomové práce anglicky:

Modeling of optical communication infrastructure building for energy distribution network operator

Pokyny pro vypracování:

Analýza současného stavu budování optických sítích v energetice (Smart Grid), dopadů národního plánu NAP SG v ČR, speciálně pro území metropolitního provozovatele distribuční soustavy. Aktualizace plánu výstavby optické sítě na úrovni VN a NN při zahrnutí požadavků řízení energetické sítě (Smart Grid), měření odběrných míst (Smart Metering) i obecné datové služby (Internet). Rozbor vhodných technologií pro pasivní i aktivní část optické sítě. Modelování výstavby optické sítě pro různé varianty. Vytvoření nákladového modelu a provedení optimalizací. Aplikace vytvořeného modelu ve vybrané lokalitě.

Seznam doporučené literatury:

[1] National Action Plan for Smart Grids (NAP SG), Ministry of Industry and Trade (MPO), 2019.
[2] Internal sources of metropolitan Distribution system operator (PREdi).

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Abstrakt

Jednotnou myšlienkou pojmu inteligentnej siete je, že všetky objekty využívajú automatizovaný systém riadenia energie na vzájomnú komunikáciu, reguláciu svojich energetických požiadaviek, ukladanie nevyužitej energie a dodávanie vlastnej vyrobenej energie do siete. To znamená, že elektroenergetika budúcnosti bude oveľa viac informačne náročná ako dnes. Podstatou inteligentných sietí je riadenie premenných v reálnom čase. Z tohto dôvodu je jedným z kľúčových prvkov Smart Grids podporná komunikačná infraštruktúra.

Práca vychádza najmä z Národného akčného plánu pre inteligentné siete, ktorý schválila vláda Českej republiky. V prvej časti práce sa vo všeobecnosti rozoberá koncept Smart Grid, význam komunikačných technológií pre tento typ sietí a opisujú sa rôzne možnosti výberu technológií použiteľných v systémoch Smart Grid. Následne sa teoretická časť práce zaoberá predovšetkým optickými komunikáciami, stručne predstavuje typy optických vlákien a káblov a možnosti ich inštalácie v energetike.

Transformácia energetickej siete je veľkou technologickou a ekonomickou výzvou, ktorú je potrebné dôkladne naplánovať. Hlavnou časťou práce je najmä plánovanie prekryvnej optickej komunikačnej siete vybudovanej formou prípolože k elektrickej sieti na úrovni nízkeho napätia pre potreby distribútora elektrickej energie PREdi. V práci sú opísané rôzne metódy výberu nízkonapäťových silových káblov pre inštaláciu optickej komunikačnej siete vychádzajúce z teórie grafov. Metódy sú následne aplikované na rôzne vzorky dát distribučnej siete vo vybraných lokalitách. Topológie, získané pomocou rôznych metód, sú nakoniec porovnané na základe ich ekonomického vyhodnotenia.

Kľúčové slová:
Inteligentná sieť, optické komunikácie, plánovanie siete, návrh komunikačnej infraštruktúry, teória grafov.

Abstract

The unifying idea of the Smart Grid concept is that all objects use an automated energy management system to communicate with each other, regulate their energy requirements, store unused energy and supply their own generated energy to the grid. That means that the electric power industry of the future will be far more information-intensive than it is today. The essence of Smart Grids is real-time control of variables. For this reason, one of the key elements of Smart Grids is the supporting communication infrastructure.

The thesis is based mainly on the National Action Plan for Smart Grid approved by the Government of the Czech Republic. In the first part, the concept of Smart Grid in general and the importance of communication technologies for this type of grid are discussed and various options for selecting technologies applicable in Smart Grid systems are described. Then the theoretical part of the thesis in particular deals with optical communications, briefly introduces the types of optical fibres and cables and the possibilities of their installation in the energy sector.

The transformation of power grid is a major technological and economic challenge that needs to be properly planned. The main part of the work is mainly the planning of the overlapping optical communication network built in the form of an attachment to the power grid at the low voltage level for the needs of the electricity distributor PREdi. Different methods of selection of low voltage power cables for installation of optical communication network based on graph theory are described. The methods are applied to different samples of distribution network data in selected locations. The topologies obtained using the different methods are then compared based on their economic evaluation.

Keywords:
Smart Grid, optical communications, network planning, communication infrastructure design, graph theory.

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List of Acronyms

10GEPON	10 Gigabit Ethernet PON.
3GPP	3rd Generation Partnership Project.
ADSS	All-Dielectric Self-Supporting.
AMM	Advanced Meter Management.
B2C	Business-to-Consumer.
BPL	Broadband Power Line Communication.
CEN	French: Comité Européen de Normalisation (The European Committee for Standardization).
CENELEC	French: Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Standardization).
CWDM	Coarse Wavelength-Division Multiplexing.
DER	Distributed Energy Resources.
DFB laser	Distributed Feedback laser.
DSO	Distribution System Operator.
DWDM	Dense Wavelength-Division Multiplexing.
EDGE	Enhanced Data for GSM Evolution.
EMI	ElectroMagnetic Interference.
EPON	Ethernet PON.
ETSI	European Telecommunications Standards Institute.
FTTx	Fibre To The x: FTTH - Fibre To The Home, FTTB - Fibre To The Building...
GIS	Geographic Information System.
GPON	Gigabit PON.
GPR	Ground Potential Rise.
GPRS	General Packet Radio Service.
GSM	Global System for Mobile Communications.
HDPE	High Density PolyEthylene.
HSDPA	High-Speed Downlink Packet Access.
HSUPA	High-Speed Uplink Packet Access.
HV	High Voltage.
ICS/OT	Industrial Control Systems/Operational Technology.
ICT/IT	Information and Communication Technology/Information Technology.

IEEE	Institute of Electrical and Electronics Engineers.
IoT	Internet of Things.
ITU	International Telecommunication Union.
ITU-T	ITU Telecommunication Standardization Sector.
LAN	Local Area Network.
LoRaWAN	Long Range Wide Area Network.
LOS	Line Of Sight.
LPWAN	Low-Power Wide Area Network.
LTE	Long Term Evolution.
LV	Low Voltage.
M2M	Machine-to-Machine.
MAN	Metropolitan Area Network.
MIMO	Multiple Input - Multiple Output.
MPLS-TP	Multiprotocol Label Switching - Transport Profile.
MST	Minimum Spanning Tree.
MV	Middle Voltage.
NAP SG	National Action Plan for Smart Grids.
NB-IoT	Narrow Band Internet of Things.
NB-PLC	Narrow Band Power Line Communication.
NLOS	Non Line Of Sight.
OADMs	Optical Add-Drop Multiplexers.
ODN	Optical Distribution Network.
OFDM	Orthogonal Frequency Division Multiplex.
OLT	Optical Line Termination.
OSI	Open Systems Interconnection.
OTH	Optical Transport Hierarchy.
P2P	Point-to-point.
PLC	Power Line Communication.
PON	Passive Optical Network.
PON-B	Passive Optical Network to the Building.
PON-M	Passive Optical Network to the Meter.
PREdi	PREdistribuce, a. s..
PRIME	PoweRline Intelligent Metering Evolution.
QAM	Quadrature Amplitude Modulation.
QoS	Quality of Service.
RFI	Radio Frequency Interference.
S-JTSK	Czech: Systém Jednotné Trigonometrické Sítě Katastrální (Unified Trigonometric Cadastral Network System).

SDH	Synchronous Digital Hierarchy.
SGAM	Smart Grid Architecture Model.
SHDSL	Single pair High speed Digital Subscriber Line.
SMF	Single-Mode optical Fibre.
STM	Synchronous Transport Modules.
UMTS	Universal Mobile Telecommunications System.
VDSL	Very high speed Digital Subscriber Line.
WAN	Wide Area Network.
WDM	Wavelength-Division Multiplexing.
WMN	Wireless Mesh Network.
xDSL	Digital Subscriber Line.
XG-pon	10 Gigabit PON.

1 Introduction

With the ongoing trends in the energy sector such as consumption management, the use of electricity storage technologies, the advent of electromobility or decentralised electricity generation due to the use of renewable energy sources whose production can be harder to estimate in advance, Smart Grid is clearly playing a more and more important role in the electric power system industry and the deployment and use of Smart Grids will thus be an essential part of ensuring reliable operation of the electricity system in the near future. The integration of large volumes of electricity production from inconstant sources into the electricity system and the expected increase in production also from small sources connected to the distribution grid will not be possible to manage without the introduction of a new way of managing the system and Smart Grids. The use of the Smart Grid environment will also be essential for the development of the electricity market and its use by active consumers and prosumers[1]. In addition, Smart Grids will allow consumers to easily monitor their consumption and to use electricity at times when it is most convenient, thereby increasing the efficiency of energy use. [12]

In order to ensure the functioning of Smart Grids, not only legislative, tariff and regulatory conditions need to be created. Electricity system development scenarios assume innovative approaches and massive use of new technologies that require a high level of digitalization. It is necessary to digitise and automate the distribution network, particularly enabling its remote control, rapid response to fault conditions and customer requirements and effective management of the ageing and renewal of the distribution network. [19]

Transmission and distribution system operators play a key role in integrating digital infrastructure components with traditional physical elements of the electricity system. The most significant changes will occur in the distribution systems, where the concept of digitalization is mainly associated with the implementation of Smart Grids at middle voltage (MV) and low voltage (LV) levels. The digitalization of networks is a prerequisite for managing their operation with active customer involvement. This means especially the creation of new communication and data networks for network operation management, remote control, metering and signalling, the introduction of automation functions, new generations of protection, modifications in the topology of MV and LV networks and the addition of new switching elements to these networks. Therefore, an integral part of Smart Grids will be a communication infrastructure with a high level of cyber security. [19]

PREdistribuce, a. s. (PREdi) is the owner and operator of the distribution system in the territory of the capital city of Prague. Due to the growing requirements for ensuring the continuity and quality of electricity supply and the increasing share of new technologies such as electromobility, Advanced Meter Management (AMM) and others, the company aims to ensure that the distribution system is ready for the arrival of modern energy trends. The process of making the distribution network smart and the creation of smart infrastructure are carried out in accordance with the National Action Plan for Smart Grids (NAP SG) [19] approved by the Government of the Czech Republic. PREdi focuses mainly on making MV/LV secondary substations smart and on the development of fibre optic infrastructure. [3]

As mentioned above, making the grid smart and creating smart infrastructure cannot be done without communication. Therefore, a robust optical network is already being prepared in Prague for real-time control of the previously mentioned technologies. The development of the optical network will enable the company to cope with technological changes related to the growth of de-

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[1] A prosumer is an individual who both consumes and produces. The term is a portmanteau of the words producer and consumer.

centralised generation, the development of electromobility, increasing demands on the reliability of the distribution network or the expected increase in the volume of measured and transmitted data from smart metering systems. Optical infrastructure will enable faster deployment of new technologies and Smart Grids will provide consumers with technological support to increase energy efficiency. [15]

This thesis deals with the analysis of the status of the construction of optical networks in the energy sector and the update of the plan for the construction of the optical network at the MV and LV level with the inclusion of the requirements of the energy network management (Smart Grid) and metering (Smart Metering) for the needs of the distribution network operator PREdi. Primarily, the focus is on the LV part of the network in the practical part of the thesis. The aim is to model the optical network for different scenarios, create a cost model and perform optimizations, then apply the created model on data in a selected location in Prague operated by PREdi. The main objective is to connect as many stations as possible to the continuous optical network in the shortest possible time at the lowest possible cost.

2 Smart Grid concept

2.1 Smart Grid definition and characteristics

A Smart Grid is an enhancement of the 20th century power grid. The traditional power grids are generally used to carry power from a few central generators to a large number of users or customers. In contrast, the Smart Grid uses two-way flows of electricity and information to create an automated and distributed advanced energy delivery network. [12]

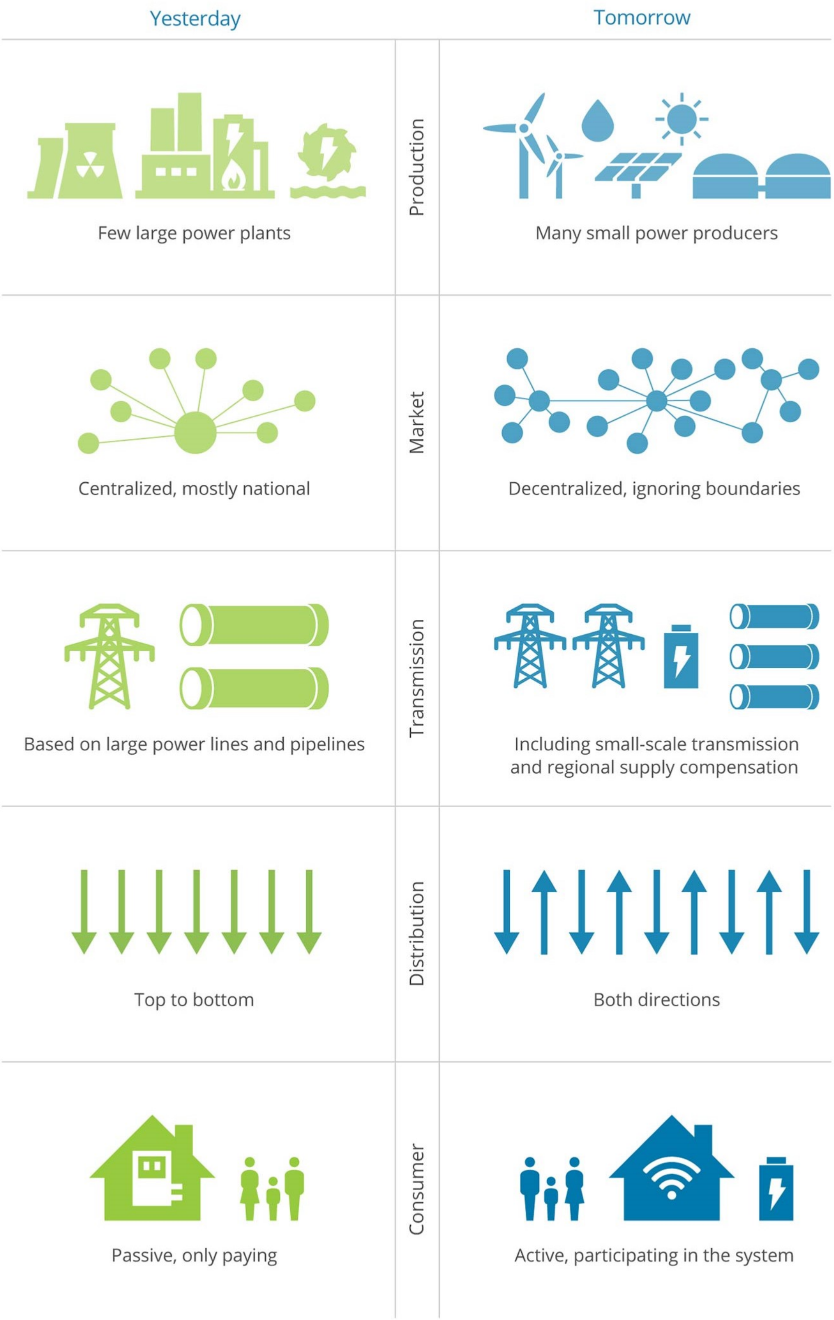

Figure 1: Staying big or getting smaller: Expected structural changes in the energy system made possible by the increased use of digital tools [8]

To highlight the most striking differences between traditional power grid and Smart Grid, the former is characterised by one-way communication, centralised power generation, low integration of distributed energy resources, low number of sensors, manual monitoring, restoration and testing, limited ability to control, low efficiency and high environmental impact opposed to two-way communication, distributed power generation, high degree of integration of distributed energy sources, high number of sensors, self-monitoring, self-reconfiguration in case of outage recovery, remote testing, pervasive ability to control, high efficiency and low environmental impact which characterise the later. [5] Figure 1 points out the most important differences between yesterday's and tomorrow's power grid. It shows characteristics of a traditional system (left) versus the Smart Grid (right).

By utilising modern information technologies, the Smart Grid is capable of delivering power in more efficient ways and responding to wide ranging conditions and events. Broadly stated, the Smart Grid could respond to events that occur anywhere in the grid, such as power generation, transmission, distribution, and consumption, and adopt the corresponding strategies. [12] More specifically, as defined in [13] the Smart Grid can be envisioned as *"an electric system that uses information, two-way cyber-secure communication technologies and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable"*. This definition covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity. As [13] states, the ultimate Smart Grid is a vision, and it will require cost justification at every step before implementation, then testing and verification before extensive deployment.

Some of the key requirements of the Smart Grid are addressed next. Smart Grids allow for the integration of renewable energy resources to address global climate change, active customer participation to enable far better energy conservation, secure communication, better utilisation of existing assets to address long term sustainability, optimised energy flow to reduce losses and lower the cost of energy, the integration of electric vehicles to reduce dependence on hydrocarbon fuels, the management of distributed generation and energy storage to eliminate or defer system expansion and reduce the overall cost of energy and the integration of communication and control across the energy system to promote interoperability and open systems and to increase safety and operational flexibility. [13]

The Smart Grid, as characterised above, does not replace the existing electric system. It builds on the available infrastructure to increase the utilisation of existing assets and to empower the implementation of the new functionality. Availability of two-way, cyber-secure, end-to-end communication systems will provide customers with the knowledge of their energy usage necessary to allow them to locally and/or remotely control their smart appliances and temperature settings. Monitoring and control of the electric system components will provide the utility with the real time status of the system. The use of this real time data, combined with integrated system modelling and powerful new diagnostic tools and techniques, will provide the detection of precursors to failure in order to drive preventive maintenance and dynamic work management systems. Distributed generation and storage resources and remotely controlled equipment will also play an important role in the management of the Smart Grid energy system, not only to address contingency needs but also to optimise power flow and minimise system losses. Building the Smart Grid, as envisioned here, will be very costly and will require a sustained implementation process that evolves over decades. [13]

2.2 Smart Grid architecture model

The European Smart Grid Architecture Model (SGAM) was developed by the Smart Grid Co-ordination Group and the European standardisation organisations CEN/CENELEC/ETSI. [10] Representing a recognised reference for classifying and discussing information systems and assets in the Smart Grid, the SGAM can serve as a basis for more indepth architecture assessment and analysis for security, costs, technical interoperability and degree of standardisation needed for technical interfaces in Smart Grids and the corresponding profiles for integration. SGAM is a methodology that helps in designing new Smart Grid's use cases and services with an architectural approach. This methodology allows a neutral representation of the involved technologies highlighting their interoperability supported by standards and, consequently, enabling standards gap analysis. For this purpose, SGAM introduces interoperability aspects and how they are taken into account via a domain, zone and layer based approach.

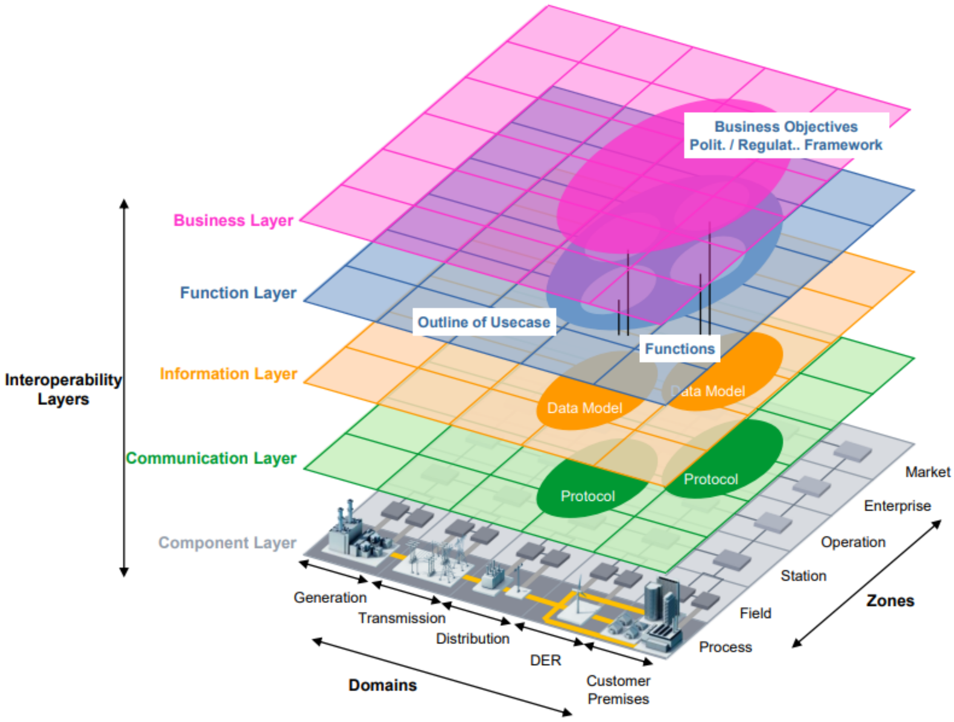

Figure 2: SGAM framework [10]

SGAM is a three dimensional model (depicted in Figure 2) that is merging the dimension of five interoperability layers (Business, Function, Information, Communication and Component) with the two dimensions of the Smart Grid Plane, i.e. zones (representing the hierarchical levels of power system management: Process, Field, Station, Operation, Enterprise and Market) and domains (covering the complete electrical energy conversion chain: Bulk Generation, Transmission, Distribution, Distributed Energy Resources (DER) and Customers Premises). A more detailed description of the model is given by [10].

2.3 Smart Grid communication challenges and the main impulses for telecommunications network development

As stated in [4], the most important challenges in Smart Grid communication are interoperability, efficiency and performance. In order to enable the real deployment of Smart Grid systems, different communication technologies for utility companies, users and suppliers should be adopted within a heterogeneous platform that allows dynamic and efficient coexistence of multiple devices and techniques. Smart Grid infrastructure will integrate different domains such as communication and networking technologies with security and energy systems. The enormous scale of Smart Grid systems involving millions of potential users worldwide requires greater scalability and Quality of Service (QoS) between wired and wireless technologies. Security and privacy will also hinder electrical grid modernization as the increasing complexity of Smart Grid communication systems requires new techniques and measurements against unauthorised access and cyber vulnerabilities. [5][4]

Recent changes in policy mean that electricity companies are under pressure to increase the amount of electricity derived from renewable sources. This has resulted in the emergence of wind turbines, photo-voltaic cells, and tidal turbines, all of which generate power at far lower voltages and connect to the grid at lower distribution levels. The implications of these few requirements are that every distributed generator and every plant item, no matter how small, may need to be monitored and controlled remotely. For example, a village of the future may have its own micro-grid supplying its own electricity locally, and only drawing energy from the main grid in times of faults or failure of wind, sun or sea waves. Therefore, these grids will need accompanying communication technology for this monitoring. [9]

The efficiency of energy network management is critically dependent on the quality and quantity of information provided from all parts of the energy system, primarily from energy sources and appliances. In order to ensure effective management, it is necessary to create a sufficiently dimensioned Information and Communication Technology (ICT) infrastructure between individual sources/appliances, control units, data centre and control room. The new directions in the development of the electricity sector are interconnected and require the cooperation of systems at several levels of the network. [11] selects the most important of them, which determine the future shape of the telecommunications network for energy:

- Central monitoring and control of power quality.
- Ensuring system operation with decentralised sources, coordinating control functions across all voltage levels with support for bi-directional power flows.
- Use of information from supply points for distribution system management.
- Optimisation of system operation, savings of technical and non-technical losses, balance calculations.
- Creating conditions for a higher degree of automation of the distribution system and for home automation.
- Support for electromobility, virtual power plants, energy storage, microgrids.
- Early identification of faults at the point of consumption.

Changes in the layout and capacity of network elements are mainly foreseen in the energy network management centre. Implementation of new functions will require strengthening of existing computing capacities, introduction of virtualization, and especially changes in software and method of processing and further distribution of data to other systems. [11]

The current Distribution System Operator (DSO) telecommunication networks provide communication of central systems with HV substations and other objects at this voltage level via the backbone and regional WAN. However, it needs to be strengthened, modernised and prepared for the increase in the volume of data from lower levels of the network. At the MV and LV level, with exceptions and pilot projects, there is no suitable telecommunication infrastructure available today (marked with a question mark in Figure 3). The telecommunication network at these levels needs to be expanded and prepared for future Smart Grid requirements. The essential task is to select a suitable solution (combination of solutions, types of technologies) for these levels of the network, plan the construction and implement a telecommunication network that meets the requirements for the development of the energy network. [11]

The levels of the telecommunication network have a direct connection to the voltage levels and objects of the power distribution system. The following diagram depicted in Figure 3 relates the distribution system diagram (left) to the basic division of the telecommunication network levels (right). [11]

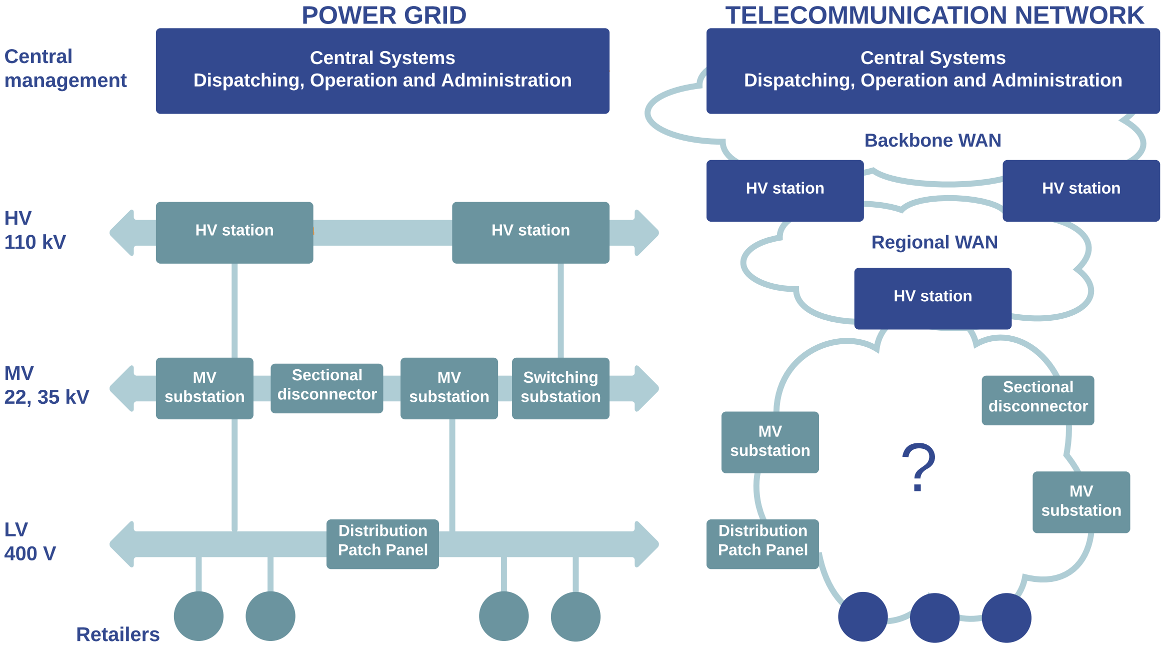

Figure 3: Distribution system and basic division of telecommunication network levels [11]

2.4 Telecommunication networks for Smart Grid

Telecommunication networks for the power industry are primarily subject to the same requirements as networks for general use. They need to be built on international standards to ensure interoperability and long-term sustainability. Networks must meet the required performance parameters, allow scalability for different types of communication requirements, and ensure high reliability and security. In particular, they must meet the specific needs of the energy sector and be adapted for communication using protocols for control, monitoring, and measuring points of the energy network.

Technological communication networks for the electric power industry have always used robust systems based on established telecommunication technologies (e.g. SDH) that guarantee guaranteed throughput, deterministic delay, predictable delay variations and high reliability through redundant paths. There is little change in the network setup and configuration changes are sporadic. These technologies are becoming obsolete and unsupported by manufacturers. Protocols for power network management and support are gradually moving to TCP/IP packet communication in a similar way as they are operated in general ICT networks.

[11] states a number of differences between general ICT/IT (Information and Communication Technology/Information Technology) networks and ICS/OT (Industrial Control Systems/Operational Technology) technological networks:

- The technological communication network serves exclusively for control and support of the distribution system operation, i.e. communication of electrical stations with technical control rooms (telemetry, remote control, metering, etc.), and also for horizontal communication of equipment between these electrical stations (communication of line protection, automation, etc.).
- The technological network must respect specific operating conditions, industry standards and ensure the required quality of communication services and security.
- Technological networks are used to ensure industrial processes, communication of specific equipment and systems, they use different interfaces and communication services, communication takes place in real time, in a specific environment with higher demands on resilience, reliability and lifetime of equipment.
- For the design, delivery and commissioning of the technological network for the control of the electricity distribution system it is necessary to have appropriate practical experience in this particular area and appropriate electrical engineering qualifications (to respect the risks of electric shock when installing equipment in the premises where the electricity distribution equipment is located).
- The technological network for the purposes of dispatch control of the electrical distribution system is an essential part of the distribution system operation. It is critical for securing the supply of electricity to a large number of customers, and the economy and security of the state depend on its functionality. The DSO has legal obligations to ensure the security of electricity supply. In the event of non-compliance, it faces penalties and, if necessary, revocation of the licence for the operation of the distribution system. The DSO must minimise the risks of possible malfunction of the technological network by means of relevant technical, operational and organisational measures.

Due to the above specifics, the technological network for ensuring the operation of the distribution system must be conceptually designed as independent, physically and operationally separate from the office network and networks for commercial purposes.

2.5 Transmission media and technology types applicable in Smart Grid

Smart Grids are achieved by overlaying a hierarchical communication infrastructure on the power grid infrastructure. The design and implementation of a secure and cost-effective electricity supply network requires the integration of an efficient, reliable, and interoperable communication subsystem. The Smart Grid consists of many different types of networks and a communication subsystem in a Smart Grid must satisfy the basic requirements. As mentioned in previous chapters, the communication subsystem must support the QoS of data, it must be highly reliable and pervasively available and have a high coverage. This is mandated by the principle that the Smart Grid can respond to any event in the grid in time. The communication subsystem must also guarantee security and privacy. [12]

In general, there are three basic types of transmission media used in telecommunications in various modifications and typical communication systems that use them: metallic transmission lines, optical fibre transmission media and radio media. In general, a variety of communication systems using higher layer communication protocols, typically TCP/IP, are operated on these transmission media. [11]

Each of the transmission media, types of technologies and types of networks has certain characteristics and it is possible to evaluate the advantages and disadvantages for a given purpose. For example, radio systems, which do not require the construction of a special transmission environment, are specific because they use free space. This brings a great advantage in terms of efficiency and speed of network construction, on the other hand the disadvantage of possible interference (accidental or targeted) and the risk of eavesdropping. [11]

In the following text, the focus will primarily be on the media and technologies that, according to [11], are suitable for the construction of telecommunication networks to support distribution companies in the current state of the art and which can potentially be used in the form of services provided.

2.5.1 Metallic communication lines with xDSL technology

The Digital Subscriber Line family of technologies is designed for metallic communication lines. Digital Subscriber Lines, referred to as xDSL, use existing metallic symmetrical pairs designed for legacy fixed telephone lines. The use of metallic lines requires the installation of xDSL modems (Ethernet extenders - interface converters, or Ethernet switches equipped directly with the ports).

According to [11], symmetrical system variants are suitable for industrial networks (original signalling, control and telephone cables, provided that they are in a technically satisfactory condition - old cables are often interrupted and show leakage due to moisture intrusion, crosstalk and higher susceptibility to interference):

- SHDSL (Single pair High speed Digital Subscriber Line) - possible transmission rates from 192 kbit/s to 2312 kbit/s over distances of km,
- SHDSL.bis (Second generation of SHDSL - referred to also as G.SHDSL.bis) - higher transmission performance (up to 5,69 Mbit/s) by introducing new modulation principles,
- VDSL2 (Very high speed Digital Subscriber Line) - even higher transmission rates in tens to hundreds of Mbit/s over distances of typically hundreds of metres to 1,6 km,
- G.fast (Fast Access to Subscriber Terminals) - rates up to 1 Gbit/s over distances of 100 to 200 m.

Connections from the xDSL family are primarily used by telecommunication network operators to implement public Internet access services on the original telephone cables, but nothing prevents their use in private networks on energy companies' own communication cables previously used for telephone services and telemetry. However, new construction of metallic cables in MAN and WAN networks is not viable. [11]

2.5.2 Use of power lines for data transmission

For communication in the power grid NAP SG also proposes to use power lines as a transmission medium. Current PLC (Power Line Communication) technologies are divided into Narrowband (NB) and Broadband (BB or BPL) according to the frequency band used and its usual width.

PLC systems

PLC utilises the power transmission lines to transmit data. High frequency signals from a few kHz to tens of MHz are transferred over the power line. Narrowband systems (usually referred to simply as PLCs) typically operate in the 3 to 500 kHz band (in Europe, the bandwidth is limited to 3 kHz to 148,5 kHz). The original systems used frequency keying methods for transmission and typically offered transmission rates in the units of kbit/s. Today's NB-PLC systems use OFDM (Orthogonal Frequency Division Multiplex) modulation using multiple carriers, and thus achieve rates of tens (for current bands) to theoretically hundreds of kbit/s (with possible bandwidth expansion into the hundreds of kHz). [11]

Initial cost of PLC is lower since it uses already existing power line infrastructure. The communication network can be established quickly and cost-effectively. PLC can provide an extensive coverage, since the power lines are already installed almost everywhere. The technology is mature and has already been in use for decades for commercial broadband and is highly reliable. PLC provides high throughput and low latency which makes it suitable for Smart Grid communication in densely populated areas. [5][14]

PLC communication is mostly used on LV lines between the concentrator in the secondary substation and the smart meters. The range is highly dependent on network topology, interference level, and cable condition. One repeater section (the distance between adjacent communicating points - each can act as a signal repeater for other points) is typically several hundred metres. The technology is suitable for wide area deployment in an AMM network but fails in selective deployments due to the lack of signal repeater points. The transmission conditions are worse on overhead lines and at transitions between ground and overhead lines. [11]

High noise sources over power lines (e.g. electrical motors, power supplies, fluorescent lights, radio signal interferences) are a major concern with this form of communication. Signal attenuation and distortion due to reasons such as physical topology of the power network and load impedance fluctuation over the power lines are another disadvantage with PLC. In addition, there is significant signal attenuation at specific frequency bands due to wave reflection at the terminal points. Since power cables are not twisted and use no shielding which means power lines produce a fair amount of Electromagnetic Interference (EMI) and such EMI can be received via radio receivers easily, there are also some security concerns for PLC. [5][14]

For the emerging IEEE 1901.2 standard on NB PLC there are two proposals regarding the Physical and Medium Access Control Layer:

- PRIME (PoweRline Intelligent Metering Evolution) represents a public, open and non-proprietary telecommunications architecture, massively deployed OFDM PLC technology that ensures interoperability and backward compatibility among equipment and systems, technology which supports present and future AMM functionalities and enables the building of Smart Grids. PRIME defines lower Open Systems Interconnection (OSI) model layers of a PLC data transmission system over electricity grids of up to 1 Mbps. PRIME specifications now support frequency ranges going from the CENELEC A-band (<95kHz) up to 500 kHz, allowing for optimum usage in electric grids. Robust transmission modes have been designed to improve system performance against both high power impulsive noises and interfering noise. PRIME can be fitted for multiple applications (IEC 61334-4-32, IPv4, IPv6) enabling a variety of services beyond smart metering. [7]

- G3-PLC is an open, international standard published by the International Telecommunication Union ITU. G3-PLC meets the technical and reliability requirements necessary in the environment of PLC because of its features such as a mesh routing protocol to determine the best path between remote network nodes, a “robust” mode to improve communication under noisy channel conditions and channel estimation to select the optimal modulation scheme between neighbouring nodes. Furthermore, its support of IPv6, enabling easy integration of various application profiles, adds high versatility. G3-PLC supports frequency bands worldwide (10 kHz to 490 kHz). [6]

BPL systems

The BPL (Broadband Power Line) family of technologies uses a frequency band in the order of MHz (2 to 12 or 30 MHz, in indoor distribution up to 50 or 100 MHz), which corresponds to the transmission rate which can reach tens to hundreds of Mbit/s over short distances of tens of meters. [11]

On LV lines, BPL is used similarly to narrowband technology for communication between the concentrator in the secondary substation and smart meters. As with narrowband communication, the range is highly dependent on the network topology, the level of interference and the condition of the cables. A single repeater section is typically a few hundred meters. The technology is therefore also suitable for wide area network deployment but fails in selective deployment. The transmission conditions are worse on overhead lines and at transitions between ground and overhead lines. [11]

At the MV level, the BPL is used to interconnect secondary substations, i.e. to implement a connecting metropolitan network until the installation of optical cables within the gradual reconstruction of power infrastructure (addition of optical cables to new power cables or power cables with integrated optical fibres). [11]

The disadvantage of BPL communication over MV is the necessity to install coupling elements that must be adapted to high voltage levels. [11]

There are two ways of binding the signal to the line:

- capacitive to MV cable cores and to overhead lines (typically higher coupling efficiency, potential space problems during installation),

- inductive to the cable ground sheath (typically easier to install, potential problem with broken cable sheaths).

The range here is also dependent on many factors, one repeater section is typically hundreds of meters, maximum about 1,5 km on cable lines in P2P configuration with capacitive coupling. On overhead lines, the distances are in a large percentage of cases higher than the BPL range, so signal repeaters have to be inserted, making the installation considerably more expensive. In addition, when installing smart meters equipped with BPL communication, there may be a problem of mutual interference with domestic BPL adapters in the future. [11]

2.5.3 Optical fibre communication

Technologies based on fibre optic communication are of fundamental importance for the construction of communication networks for the energy sector in the long term. Optical fibres (optical waveguides) use the propagation of an optical signal (light beam) in the infrared region (typical wavelengths in telecommunications are 1310 and 1550 nm). The electrical signal is converted into an optical signal by an LED diode or a semiconductor laser and is coupled into a quartz glass-based fibre. On the other side, the optical signal is fed to a detector (photodiode) and converted back to an electrical signal. [11][14]

Optical fibre communication systems offer significant advantages over traditional copper-based communication systems. In electric system automation, an optical fibre communication system is one of the technically attractive communication infrastructures. The advantage of optical fibres (so-called single-mode fibres, which are used in telecommunications) is a very high bridging distance, typically in tens of km (up to over 100 km), very high transmission rate, typically in tens to hundreds of Gbit/s and the possibility of multiple use by means of the so-called wave multiplex (multiple signals at different wavelengths tied into a single fibre, which will bring a further increase in capacity ten to a hundred times).[14]

Transmission capacity and long range of optical fibres:

- current communication systems - range 120 km, bandwidth 4 THz (for two-level code-rate 2 Tbit/s),
- future communication systems - range 180 km, bandwidth 8 THz (for 64-QAM modulation and transmission using double polarisation - rate 96 Tbit/s).

Optical fibre can typically bridge 2 to 3 orders of magnitude greater distances and achieve 3 to 4 orders of magnitude higher transmission rates than other transmission media. Furthermore, optical fibre communication systems support long distance data communication with a smaller number of repeaters compared to traditional wired networks. This leads to reduced infrastructure costs for long distance communication that substation monitoring and control applications demand. In addition, its Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) immunity characteristics make it an ideal communication medium for middle voltage operating environments in substations. [11][14]

From a general point of view and due to the requirements for transmission capacity, optical fibres are necessary for HV backbone networks and suitable for MV backhauls, especially for selected locations with expected more advanced automation functions.

Although optical fibre networks have several technical advantages compared to other wired networks, the cost of the optical fibre itself is still expensive to install for electric utilities. However, the enormous bandwidth capacity of optical fibre makes it possible for substations to share the bandwidth capacity with other end users which significantly helps to recover the cost of the installation. In this respect, optical fibre communication systems might be cost-effective in the high-speed communication network backbone since optical fibres are already widely deployed in communication network backbones and the cost is spread over a large number of users. As a result, optical fibre networks can offer high performance and highly reliable communication when strict QoS substations communication requirements are taken into account. [11][14]

A joint rollout of utility and telecom networks can have a positive impact on the total cost of a network rollout. Namely the electric Smart Grid and FTTH could generate mutually beneficial scenarios. Deploying multiple utility and telecom networks together has several advantages. It reduces the total time spent by contractors to deploy the networks. This results in reduced nuisance for inhabitants and small companies located in that area, who experience the most hindrance. A more important result of this reduced work time, more interesting for network operators, is the reduced cost. [20]

The topic of optical fibre communication in the context of SG is further developed in chapter 3.

2.5.4 Radio communication

Radio systems use free space typically in point-to-point, point-to-multipoint, or multipoint (Mesh) arrangement. The radiation of the signal into space is accomplished through antennas. As the only transmission medium, free space enables mobile communication.

For radio systems, the frequency band in which the communication is operated is important, as it determines the range, the ability to propagate over obstacles - Line of Sight (LOS) propagation, Non Line of Sight (NLOS) propagation, and the level of interference. Generally, in the lower frequency bands (hundreds of MHz), the signal propagates over greater distances and penetrates better through obstacles (typically buildings) than signals in the higher bands (units of GHz). This means lower required base station network density when building area coverage using lower frequency bands and thus lower costs for building a radio network. [11]

We can distinguish bands:

- with a general licence (so-called unlicensed) - no individual licence is required for operation (typically Wi-Fi networks),
- with an individual licence (so-called licensed) - more suitable for providing communication where a guarantee of transmission parameters is required (typically mobile networks).

As a matter of priority, it is appropriate to use own radio networks in the licensed bands for the management of the energy network. However, own networks are more expensive to build and operate. It is necessary to address frequency acquisition, frequency planning, modelling and coverage measurement, location of base stations and antennas. [11]

Communication using the services of public operators

Telecommunications operators provide various services. The risk of these technologies is the dependence on the telecom operator.

Mobile networks, in addition to user mobility, bring advantages for M2M (Machine to Machine) communication at a fixed point due to their coverage of an area approaching 100% of the populated areas. [11] provides a brief description of different generations:

GSM (Global System for Mobile Communications) – standardised second generation (2G) technology for digital cellular mobile radio telephone systems for various frequency bands (900, 1800, 1900 MHz in the Czech Republic). After 2028, a gradual decline and transition to 4G and 5G networks is expected.

The following extensions (2.5G) are used for data transmissions:

- GPRS (General Packet Radio Service) – enables data transmission in the mobile network through packet switching. It allows data transmission at theoretical rates of up to 171 kbit/s.
- EDGE (Enhanced Data for GSM Evolution) – is an extension of the GPRS principle with the possibility to use multi-state modulation. The total theoretical transmission rate has been increased to 384 kbit/s.

UMTS (Universal Mobile Telecommunications System) – Third Generation (3G) mobile telecommunications system (this generation has already been switched off in the Czech Republic and is therefore presented only for the sake of overview). In theory, it is possible to achieve rates of 384 kbit/s with full mobility (in vehicles up to 120 km/h) and up to 2 Mbit/s with limited mobility (walking less than 10 km/h).

- HSDPA (High-Speed Downlink Packet Access) – is an enhancement of the UMTS network. Theoretically, it allows to achieve a transmission rate of up to 14,4 Mbit/s for a terminal with limited mobility and 1,8 Mbit/s for a terminal with full mobility.
- HSUPA (High-Speed Uplink Packet Access) – focuses on high-speed data transfer in the direction of the end user. It can achieve a theoretical transmission rate of 5,76 Mbit/s.

LTE (Long Term Evolution) – mobile wireless technology of the fourth generation (4G), which is designed for high-speed data communication in tens to hundreds of Mbit/s (in the Czech Republic, so far the 800 MHz and 2,6 GHz bands and the gradual use of the original GSM and UMTS bands). The highest transmission rates are achieved using the MIMO (Multiple Input - Multiple Output) diversity communication technique.

- LTE-A (LTE Advance) offers a theoretical throughput of up to 1 Gbit/s (using multiple bands simultaneously) and major improvements optimising the energy requirements of the entire system.
- LTE-M (LTE M2M) – LTE modification for M2M communication with lower bandwidth (1,4 MHz) and 1 Mbit/s rate in semi-duplex mode, but with a much simpler and cheaper modem.
- NB-LTE-M (Narrowband LTE) – an even more economical variant designed for IoT (also NB-IoT) with 200 kHz bandwidth and 0,2 Mbit/s rate in semi-duplex mode suitable for devices requiring low power consumption and very long battery life.

The 700 MHz band and the 3,7 GHz and 3,5 GHz bands are used for further development of 4G and 5G networks.

5G is the fifth generation of mobile network. It is designed for improved connectivity, rate, capacity and overall performance. One particularly significant characteristic of 5G is its low latency. 5G is also more reliable than 4G, with increased availability in areas with limited fixed infrastructures. Plus, 5G is more flexible, with different characteristics adapted to meet the requirements of specific applications. These characteristics make 5G potentially suitable for use in Smart Grids.

IoT technologies

[11] also mentions IoT (Internet of Things) technologies. These are wireless communication technologies that cover a large geographical area in order to connect a large number of end devices. They are also referred to as LPWAN (Low-Power Wide Area Network).

IoT technologies can be divided according to the band in which they communicate into technologies in the licensed band and technologies in the unlicensed band:

- Licensed technologies are mostly developed and prepared under the auspices of the 3GPP (3rd Generation Partnership Project) standard and include mainly NB-IoT operated by mobile operators.
- Unlicensed technologies use the 868 MHz band. There is a relatively large number of technologies. NAP SG mentions the following:
  - LoRaWAN – broadband technology based on LoRa (Long Range) modulation and standardised by LoRa Alliance. There are public networks in the Czech Republic, or private LoRa networks can be installed.
  - SigFox – narrowband technology, global network of a single operator, in the Czech Republic the integrator is currently SimpleCell.
  - WMN (Wireless Mesh Network), one of many low-power wireless technologies with mesh topology.

The main features of these technologies include low energy consumption, affordability of terminal equipment and services, but low data throughput and risk of interference.

[11] proposes LoRaWAN technology for the power industry. This technology can be used for transmissions with very low requirements, e.g. for indicating the status of fuses in LV distribution cabinets.

The NB-IoT technology is gradually developing and improving and will become the basis of IoT even within 5G networks. It is therefore promising for metering and other low data traffic. [11]

2.5.5 Technology selection

Both wireless and wired communication technologies are applicable in Smart Grid. Most power systems use a combination of different wired and wireless technologies, depending on the infrastructure. Several factors need to be taken into account when deciding on communication technology used in Smart Grid. Both types of communication are necessary in a Smart Grid environment. The technology that fits one environment may not be suitable in a different environment. Technologies must be selected with regard to expected transmission capacities, but also other parameters (transmission delays, reliability, resistance to interference and cyber attacks). [12][13]

Based on the analysis in [11], optical systems are the only suitable solution for the HV level of the power grid. Optical systems are also the preferred option for connection at the MV level. An alternative here may be BPL systems on cable lines, and in the case of distribution points, temporarily xDSL on the actual metallic communication cables. Alternatively [11] suggests proprietary radio technologies or mobile networks with sufficient security and backup.

According to [11], in general it can be stated that optical systems and networks will be used for higher levels of the network (backbone, backhaul) where there is a higher concentration of traffic (pooled data flows from multiple network points) and where there are higher requirements for response and reliability. At the same time, optical networks are preferably used in types of areas with a higher concentration of communicating points (agglomerations, cities, municipalities). This is because their construction is not efficient in areas with a low density of points, where distances are too long and thus networking costs are too high (rural areas, dispersed housing).

Communication over PLC/BPL power lines or radio (mobile) networks is suitable for the consumption points depending on their nature. Prospectively, the use of optical fibre in this level of the network can also be considered here if the density of end points is sufficient (combined Fibre to the x (FTTx) solutions). As fibre networks are expanding very rapidly also at the access level (FTTx solutions), making them more accessible and cheaper, this solution was added as aanoone of the options for connecting the customer sites in the second phase of NAP SG.

Specifically, [11] states two possible designs which are considered in the form of a so-called Passive Optical Network (PON), depending on the type of shared units:

- PON-B (Passive Optical Network to the Building) – optical fibre is terminated in the building (distribution patch panel at the base or in the basement of the building). This solution is suitable for apartment buildings with a larger number of subscriber points, typically for panel and apartment buildings and buildings in city centres. This corresponds to the large-scale coverage of AMMs in predominantly agglomeration and city type areas.
- PON-M (Passive Optical Network to the Meter) – the optical fibre is terminated at the meter in the house or near it (optical termination at the foot of the house or at the meter cabinet), which is suitable for apartment buildings with typically one point of consumption (residential buildings, family houses). This corresponds mainly to the outskirts of agglomerations and cities, which are areas relevant for DER installation.

The use of optical fibres is not considered in villages and scattered buildings.

The following chapters mostly develop the topic of optical networks in the context of Smart Grid - the importance of optical networks for Smart Grids, optical fibres and cables, installation methods etc. The practical part of the thesis is also dedicated to optical networks in the Smart Grid environment, namely to the design of optical network at the LV level.

3 Optical communication in Smart Grids

3.1 The need of optical communication in Smart Grid systems

In the previous chapters we pointed out that the communication network within the distribution company environment needs to undergo transformation and that the integrated communication infrastructure is a fundamental requirement for the other key technologies in the functioning of the Smart Grid.

The actual electrical grid already has a communication network supporting its operations between substations and control centres but this network is according to [4] expensive, uncompromising and insufficient because it covers only generation and transmission segments.

If real-time demand side management is to be used effectively, the control and communication networks must extend to all customer points. Similarly, if customers are to be encouraged to become generators (so called prosumers – *"the consumers who also produce and share surplus energy with grid and other users"* [22]), an additional data stream must be aggregated to the network extending to the home. And if both distribution company and customer control are to be supported, data requirements increase even more.

As mentioned in previous chapter, technologies based on fibre optic communication are of fundamental importance for building communication networks for the energy sector in the long term. From a general point of view and because of the transmission capacity requirements, optical fibres are necessary for HV backbone networks and suitable for MV backhauls, especially for selected sites with expected more advanced automation functions.

At its edge, the network does not need to have very high capacity. But it must have high service penetration. One can envision a mix of technologies at the edge, with an aggregation into a core network that is built on optical fibre. [9]

Data collection and real-time analysis become a more fundamental part of the business model. Hence, distribution companies require a far greater degree of visibility and control deep within the distribution network. Optical networks play an essential role in supporting the information exchange requirements between customers, the distribution network, and the data centres carrying out the real-time analysis of the data. The aggregated volume of data is unlikely to be supported without a fibre infrastructure in some parts of the distribution network. [9]

Below are two examples where an optical communication network is required as a consequence of the traffic engineering of the network – smart metering and reducing the vulnerability to intra-substation EMI and RFI inherent in copper cables. Historically, copper interfaces between the teleprotection equipment and multiplexers transfer critical information to the command centre. As mentioned also in the previous chapter, these high-speed low-energy signal interfaces are vulnerable to EMI and RFI, signal ground loops, and ground potential rise (GPR). All these factors significantly reduce the reliability of communication during electrical faults. [9]

On the other hand, optical fibres do not have ground paths and are immune to noise interference. That makes optical data links a superior interface for intra-substation communication. Replacing copper interfaces with optical fibre ensures isolation from dangerous GPR, prevents induced electrical noise, and eliminates the signal ground loops and data errors common to electrical connections. [9][14]

Although communication is not the fundamental activity of electric utilities, a Smart Grid requires a communication system with the capacity to support traditional utility functions and the flexibility to adapt to new requirements mentioned previously, such as advanced metering, demand response, distributed generation, and others. Thus, optical communication and fibre optics play a crucial role in the overall modernization of the communication architecture and infrastructure attached to the grid, thanks to its robustness against radio and electromagnetic interferences making it a suitable choice for middle voltage environs, and its capacity to transmit over large distances with very high bandwidth.

[11] lists fibre optic systems as the only suitable solution for the highest levels of the HV network. Optical systems are also the preferred option for connection at the MV level. BPL systems on cable power lines can be a temporary alternative here. Alternatively, proprietary radio technologies or mobile networks with sufficient security and backup can be used. All 3 main groups of technologies are applicable at the LV level and their choice depends primarily on site-specific conditions.

According to [11], building fibre-optic networks may also make sense at the LV level, especially where there is potential for cooperation with a commercial entity that plans to provide connectivity in the B2C (business-to-consumer) segment, especially high-speed internet. Such an entity would then participate in building the fibre infrastructure, thereby reducing costs and making the fibre solution more attractive for the location.

3.2 Optical fibres and cables

As mentioned above, optical systems stand out significantly in terms of long-term perspective and communication possibilities. This chapter makes some practical notes and highlights the types of fibre and cable suitable for access networks.

Optical fibres

Next, 4 basic types of fibre standardised in recommendation G.652, which was issued as one of recommendations in the series G.651 to G.657 by ITU-T to unify the basic parameters and characteristics of optical fibres from different manufacturers, are listed:

- type G.652.A and G.652.B fibres - older type fibres containing an attenuation peak (so-called water peak) at a wavelength of 1383 nm caused by the presence of OH- ions from production,
- type G.652.C and G.652.D fibres - more modern fibres without this peak. These optical fibres, which can use for transmission all so-called transmission windows (wavelength bands) from about 1260 nm to 1675 nm, are often referred to as allwave fibres.

G.652.D fibre eliminates the water peak for full spectrum operation. Conventional G.652.A and G.652.B are not optimised for Wavelength-Division Multiplexing (WDM) applications due to the high attenuation in the E-band region (1360-1460 nm), which is the water peak band. The G.652.D fibre has been developed to specifically reduce the water peak at the 1383 nm wavelength range. So G.652.D fibre can be used in the wavelength regions 1310 nm and 1550 nm and supports Coarse WDM (CWDM) transmission. In practice, it is now possible to meet almost exclusively with type D fibres (with types A, B and C only marginally in older applications). G.652.D fibres are nowadays standardly used for the construction of optical routes in the access network, especially for the sections from the OLT to the splitter(s) and also between splitters, the so-called feeder and drop sections. [1]

Single-mode fibres with reduced sensitivity to bending according to ITU-T G.657 recommendations are briefly described below. These are conceptually based on standard G.652 D fibres, so they do not have a modified dispersion characteristic. G.657 fibre is designed to be compatible with G.652 fibre but is less bend-sensitive, which means it produces lower levels of attenuation due to bends. The fundamental change is therefore to reduce their sensitivity to macro-movements. ITU-T Recommendation G.657 thus sets maximum attenuation values at two wavelengths (1550 nm and 1625 nm) and in the band 1530–1565 nm when winding a defined number of fibre turns with a given bending radius. Reduction of sensitivity to fibre bending is achieved by means of specifically modified refractive index profiles and other structural modifications. Recommendation G. 657 defines two groups of fibres, A and B. G.657 fibre is thus split into two parts - category A for access networks and category B for the end of access networks in bending-rich environments - according to different requirements for the maximum increase of fibre attenuation at a defined bending radius and there are also differences in the design of the fibre itself and the geometric dimensions of the fibre core and sheath. [2]

The primary purpose of fibre according to ITU-T G.657 recommendations is mainly access networks and more specifically their last sections from the local distribution patch panel to the subscriber socket, so-called distribution sections, such as wiring in buildings and facilities and wherever fibre needs to be bent in grommets, gutters, beams, end-user premises, etc. However, for feed and intermediate sections, it is more advantageous to use the standard fibre type according to G.652 D recommendations due to lower cost and easier welding, as these sections are often straight or only with large bend radii and the benefit of G.657 fibres with reduced sensitivity to macro bends would be negligible here.

Optical cables

Optical cables can be divided according to various criteria, their structural arrangement, number and types of fibres, methods of design of protective layers, etc. In terms of the way fibres are laid, cables can be divided into two basic groups:

- Loose Tube cables, i.e. with loose secondary protection,
- Tight Buffer cables, i.e. with tight secondary protection.

In both cases, the optical fibres are placed in the cable itself in various ways, usually circularly to the centre (cable core), in layers, to concentric circles, symmetrically to two (or more groups) to the centre of the cable, around the tension element, to the tapes (so-called ribbon cables), etc. In addition to optical fibres, other elements can be inserted into the cables, e.g. tensile (support) member, in addition to purely optical cables, there are also hybrid cables with a combination of optical fibres and power metallic distributions for the distribution of electricity. [17]

3.3 Optical fibre and cable laying and installation methods

A separate chapter is the laying and installation of optical cables and optical fibres. With the gradual development of optical communications and the construction of optical transmission routes not only in backbone networks, but more recently especially in access networks, a number of methods of installation and laying of optical cables and fibres have been developed and these methods have been continuously improved and refined. In this chapter, we encounter the main disadvantage of fibre optics. It is the higher installation costs, which are of course dependent on the way the cables are installed:

- Cable ground lines:
  - Cables in separate excavations,
  - Prepared HDPE tubes in the excavation,
  - Fibre optic cables or HDPE tubes as an attachment to power cables in a common excavation, cable channel or tunnel,
  - Optical fibres integrated into LV power cables.
- Overhead lines:
  - Combined ground cables for HV,
  - All-Dielectric Self-Supporting (ADSS) suspension cables on HV and MV poles,
  - ADSS suspension dielectric cables on LV poles,
  - Optical fibres integrated in LV cables.

Today, the most common installation method is the underground laying of cable ducts, HDPE tubes and microtubes, into which the actual fibre optic cables are then blown or pulled. The cable duct is a tube made of various materials, but most often of hardened plastics (HDPE). Separate HDPE tubes or microtubes can be placed in it to perform its sectorization. In many cases it is sufficient to lay only HDPE tubes or even just the microtubes themselves (with more resistant sheath) instead of cable ducts. In addition to these basic elements, in practice, it is necessary to solve the bends of the route (tubes, multichannels), the location of grommets, the connection of tubes, microtubes and multichannels, as well as their branching, coupling, etc. (e.g. T-couplers, Y-couplers), location of ground chambers (e.g. for hubs) and other accessories necessary for successful construction of an optical distribution network. [17]

In addition to the actual optical routes, it is also necessary to install so-called cable access chambers, which allow access to the given optical cables and fibres for the needs of their inspection, measurement, repair, replacement, installation of new ones, etc. Another common element of optical networks is coupling chambers, above-ground pillar cabinets and panels (switchboards). These are built at key nodes of the Optical Distribution Network (ODN) and are used for placement of optical hubs, couplers, optical panels with connectors for connection of individual sections and end users, etc. The necessary reserve of optical cables and fibres on a given optical path is often also placed in them. The pillars always have a corresponding underground part, into which protective HDPE pipes or directly microtubes with the optical micro cables are introduced by means of sealed grommets (against water and moisture penetration). The pillar cabinets can usually be equipped with a variety of cassette systems for attaching and positioning fibre optic cables and fibres, fibre optic panel and connector supports and other optional elements for easy management of fibre optic cables, connectors, hubs, etc. [17]

Sufficient flexibility of ODN (the possibility to implement diverse optical routes by means of interconnection in cabinets), reserve for the future and openness for different technologies (point-to-point and multipoint optical links, passive or active networks according to different standards and specifications) and possible alternative operators (sharing of the access network, renting part of the capacity of optical cables, etc.) are of high importance. [17]

Although the construction of an optical network is expensive, optical technology is generally considered to be the most advanced and promising technology. Optical technology may have higher acquisition costs, but in the long run it brings savings, at least at the level of HV and MV, because the most expensive part of the optical network - optical cables - have significantly higher lifetime and lower operating costs than active elements of other technologies. [11]

Costs are significantly lower for fibre optic cables attached to power cables and overhead cables compared to cables in separate excavations. They vary quite significantly depending on the nature of the terrain, the local situation and the need to deal with administrative obstacles. [11]

In the case of synchronisation of the optical network construction with the power network renewal, a separate action (laying) does not have to be realised, but only the optical network element is added, which is approximately 5-6 times cheaper than a separate action. The reason for such a substantial price difference is the absence of the cost of the excavation work, as this would have been done anyway for the power part and therefore the multi-cost is so low. In contrast, in a stand-alone event, excavation work has to be carried out specifically and only for the construction of the fibre network, which makes the network very expensive. [11]

The situation is somewhat different at the LV level, where the technical superiority of optical networks is undoubtedly still present, but the contribution of such high-quality technology for network management is not as significant as at the HV or MV level. On the other hand, radio technology loses its competitive advantage of fast roll-out here, as roll-out is likely to take place together with the replacement of meters for calibration reasons. The BPL/PLC technology also offers a satisfactory solution but can only be deployed when a certain density of communicating points is reached, otherwise additional repeaters would have to be used, which would have a strong negative impact on cost increases. [11]

PREdi specifically operates a metropolitan distribution network with almost exclusively MV and LV ground cables. This allows for an efficient fibre optic infrastructure solution using combined power-transmission cables with integrated plastic tubing for fibre optic cable blowing. [3]

3.4 Technologies for optical communications in the context of Smart Grid

[11] lists 2 different concepts which are currently dominant for the construction of optical access networks:

- point-to-point networks using Ethernet and connecting the end optical units in a star topology,
- or point-to-multipoint networks based on a passive distribution of optical signals and the implementation of tree topology using passive splitters.

3.4.1 Point-to-point optical networks

A common optical link design is based on a point-to-point architecture, where a pair of dedicated optical fibres (each for one direction of transmission) leads to each endpoint. For cases where there is a lack of optical fibres, variants using a single fibre for both transmission directions have also been developed based on the principle of wave multiplexing (specific wavelength for each transmission direction).

The classical and nowadays obsolete technology designed for optical fibres is called SDH (Synchronous Digital Hierarchy) - transmission over optical fibres by Synchronous Transport Modules STM-N, where N expresses the hierarchical level from STM-1 (155 Mbit/s) to STM 256 (40 Gbit/s). There is no sense to consider SDH in new installations, MPLS-TP (Multiprotocol Label Switching - Transport Profile) technology is suitable as a replacement.[11]

Optical Ethernet, specified by IEEE 802.3 standards, is a promising technology for all levels of power grid. At the physical layer, both metallic (in a LAN) and optical lines can be used, thus achieving a wide range of transmission rates from 1 to 100 Gbit/s. [11]

WDM (Wavelength Division Multiplexing) is a technology in optical networks that combines multiple optical signals in a single optical fibre using different wavelengths (colours) of lasers for transmission. This makes it possible to expand the capacity of the medium or to perform bi-directional communication on a single optical fibre. Optical Add-Drop Multiplexers (OADMs) enable circular topology networks with very fast protective switching (back-up) at the wavelength level (physical layer):

- DWDM (Dense WDM) – Dense wavelength multiplex (up to 80 channels) is mainly used on long-distance optical routes. The encapsulation of Ethernet 1G, 10G, 40G and other formats is standardised as OTH (Optical Transport Hierarchy),
- CWDM (Coarse WDM) – The wider 20 nm channel can use a temperature-unstabilised DFB laser (Distributed Feedback Laser) and for this reason these systems are cheaper than DWDM but only allow 16 channels to be combined.

3.4.2 Multipoint optical networks

The multipoint solution is based on the principle of the so-called Passive Optical Network (PON) with branching of the optical signal by means of splitters. PONs use optical fibre splitting to multiple endpoints typically over a distance of 10 km. In the power industry, this technology can be used for passive splitting of fibres suspended from overhead lines. There are two standardisation directions (mutually incompatible), namely the IEEE Ethernet group and the ITU-T recommendations.

The basic selected PON specifications that [11] mentions are:

- GPON (Gigabit PON) according to ITU-T G.984 - transmission rates up to 2.5 Gbit/s, split ratio 1:64 and 1:128,
- EPON (Ethernet PON) standard IEEE 802.3ah - transmission rates 1.25 Gbit/s in both directions, split ratios 1:16, 1:32,
- 10GEPON (10 Gigabit Ethernet PON) standard IEEE 802.3av - two variants of transmission rates - symmetric with rates of 10 Gbit/s in both directions and asymmetric with rates of 10/1 Gbit/s,
- XG-PON (10 Gigabit PON) according to ITU-T G.987 - asymmetric variant of transmission rates 10/2,5 Gbit/s (symmetric variant 10/10 Gbit/s and further 40/10 Gbit/s is planned), high split ratio up to 1:256, energy-saving modes of terminal units.

PONs can be used in the power industry on outdoor MV backhauls or in metropolitan networks at LV level. A variant is to bring fibre optics via a combined power cable to the foot of the building, i.e. the implementation of FTTB (Fibre to the Building). The optical fibre can be terminated in a concentrator that takes care of the data collection from the electricity meters. Other optical fibres can be used for common communication services, typically household access to the Internet. [11]

4 Current status of the issue and goals

4.1 The main activity of PREdi

PREdi is the owner and operator of the distribution system in the capital city of Prague, the town of Roztoky and the municipality of Žalov with a total area of 505 km^2. Its main mission is to provide a reliable and secure supply of electricity to all its customers in the licensed area. The key processes and activities for ensuring reliable electricity distribution include, in particular, the renewal and development of the distribution network, connecting new customers, buildings and units, optimal operation management and troubleshooting, network maintenance and repairs, metering and other services related to electricity distribution. [3]

Due to the growing requirements for ensuring the continuity and quality of electricity supply and the increasing share of new technologies such as electromobility, AMM and storage, the company aims to ensure the readiness of the distribution system for the arrival of modern energy trends well in advance. The smartening of the distribution network and the creation of smart infrastructure is carried out in accordance with the National Action Plan for Smart Grids [4] approved by the Government of the Czech Republic. PREdi focuses mainly on the smartening of MV/LV distribution secondary substations and the development of fibre optic infrastructure. In terms of strategic investments, the planned development of the distribution network in 2021 mainly concerns the construction or modernisation of 110/22 kV substations and 110 kV overhead or cable lines in PREdi's supply area. The individual actions are based on the company's long-term distribution network development concept. [3]

The development of PREdi's Smart Grids is supported by its subsidiary PREnetcom, a. s., (PREnetcom), which is the know-how holder for building, operating and using optical data networks. PREnetcom was established on 27 November 2017 as a 100% subsidiary of PREdi and started its operations on 1 January 2018. It cooperates with PREdi on the conceptual development in the planning and coordination of the construction and maintenance of optical infrastructure. It is dedicated to the operation and development of the use of metallic and especially optical communication cables built together with the distribution system for the needs of monitoring, management and control of Smart Grids. Its main task is to fulfil PREdi's long-term strategic objective of designing and building communication links between the individual elements of the distribution network to ensure secure transmission of network data, remote control within the implementation of the Smart Grids concept and, in the future, probably also smart metering within the distribution system. Another goal of the company is to use the potential free capacity of the communication network created in this way for commercial purposes, from Smart City concepts through Smart Home to wholesale sales to third parties. [3]

4.2 Brief description of PREdi network structure

PREdi's distribution system consists of 110 kV, 22 kV and 0,4 kV overhead and cable lines measuring 12 422 km, 26 units of 110/22 kV MV substations and 4 934 units of 22/0,4 kV LV secondary substations. [3]

Middle voltage network

The MV network consists of MV cables. At present, the renewal of MV cables is carried out using new combined cables with an integrated pipe allowing the blowing of fibre optic cables/optical fibres. Approximately 100 km of cables are renewed annually within the MV cable network. For each MV cable, a so-called Renewal Index is determined, which reflects the quality of the cable and thus defines its suitability for renewal. In terms of graphs, it is a branch weight that expresses the potential for creating a new optical path between stations. This Renewal Index can be modified ”recursively” by the optimisation method (called a strategic factor) to prioritise a given cable earlier in the renewal, if the importance of the cable in the optimisation is such that it will help to connect stations within the optical network faster. [21]

The nodes of the MV network are:

- Substation 110/22 kV (26 units) – backbone optical network is available in all substations,
- Switching substation 22 kV (approx. 350 units) - optical network enabling connection to the backbone is available in approx. 250 switching substations. It is also important to get the remaining stations connected to the fibre optic backbone,
- Secondary substation 22/0,4 kV (approx. 4900 units) - optical network is available in few stations so far. The aim of the optimisation is to connect these stations to the fibre optic backbone using combined MV and LV cables,
- MV connectors - connecting two MV cable sections - the fibre optic cable only passes through.

Low voltage network

The LV network consists of LV cables. At present, the renewal of the LV cables is carried out using new combined cables with a tube that allows the blowing of fibre optic cables/optical fibres. Within the LV cable network, approximately 100 km of cables are also renewed annually. For LV cables (generally groups of LV cables - e.g. under a single station) a parameter is also defined to express their quality (age estimate) and thus determine their suitability for inclusion in the renewal. In the concept of the graph, it is again the weight of the branch, which expresses the potential to create a new optical path between stations. Based on the optimization method, this Renewal Index can be ”recursively” modified (so-called strategic factor) so that the given cable (group of cables) prioritises earlier in the recovery, if the significance of the cable in optimization is such that it will help to speed up the connection of stations within the optical network. [21]

LV network nodes consist of:

- Secondary substation 22/0,4 kV (approx. 4900 units) - the optical network is currently available in a few stations. The goal is to connect these stations to the optical backbone network using combined MV and LV cables,
- Distribution points and fuse cabinets – LV cable passes through it and in the future it will allow connection of optical fibre to the powered object,
- LV connectors - connect two LV cable sections - the optical cable only passes.

Optical network

Optical network (backbone) is a network of HDPE tubes and optical cables. The nodes consist of all 110/22 kV substations, about 250 switching substations and several 22/0,4 kV secondary substations. It is necessary for fibre optics to reach this backbone network. [21]

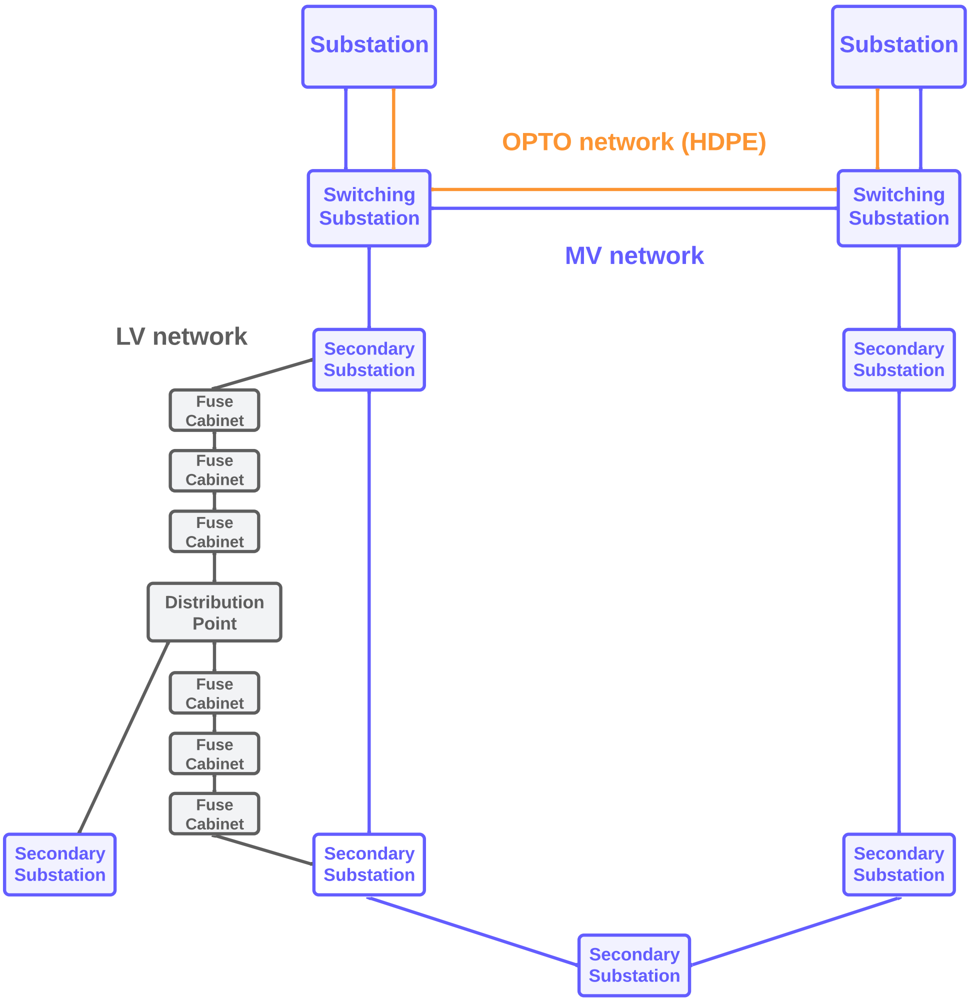

Figure 4: Optical (orange), MV (blue) and LV (grey) simplified topological network diagram [21]

Diagram in Figure 4 shows MV and LV level of power grid and overlapping optical network. Backbone optical network is available in all MV substations. Optical network enabling connection to the backbone is available in most switching substations (it is also important to get the remaining switching substations connected to the fibre optic backbone). The optical network is currently available in few MV/LV secondary substations. PREdi's goal is to connect these stations to the optical backbone network using combined MV and LV cables. Secondary substations can be interconnected with LV cables if omitting changing the MV cables between them is desirable.

4.3 Goals

Based on the development of technology, current status and estimates from a number of sources and studies, it was decided to deploy a wide area fibre optic network at the MV level (target coverage of all expansion, loop and node stations) and to prepare for the installation of fibre optics at the LV level. [21][19]

PREdi's main objective is to connect as many stations of interest as possible into a continuous network in the shortest possible time at the lowest possible cost. At the same time, a scope of construction per year is limited. At the moment, it is determined by the maximum length of laying of cables per year. The question is whether a certain amount of investment funds will be allocated (therefore the price of the network built per year will be given) and how this change will be reflected in the resulting effect.

Next chapters deal mainly with the LV part of the power grid. The latter is characterised by considerable redundancy. On the LV level of the grid, suitable tubes where the optical cables will be installed need to be selected, i.e. we need to select a suitable subset of LV network links taking into account parameters of individual LV cables defining the suitability of cable inclusion in the restoration.

First of all, each substation will be considered an end point - fibre optics will be introduced to all endpoints (all entrances/houses).

There is also a second possible scenario in which optics can be introduced to every third entrance or every second entrance. We can imagine using BPL technology with a concentrator that has a certain range thus it can serve both left and right entrances via power cables.

The aim is to determine the impact on the reference indicator, i.e. to compare different approaches and determine which one is more optimal or cheaper.

5 Optical infrastructure design methodology

5.1 Starting points

The thesis is mostly based on the consultations of the problem with the consultant in the field of energy, self-study of the background research, study of general methods over graphs and data provided by PREdi.

Redundancy of power grid

The power grid topology is characterised by typical redundancy. In the past, booster cables were added to the network and therefore, for the optical infrastructure, cables will be selected where the installation will cost the least. The optical network will overlap with the LV network, so there is no need to create redundancy. The first target will be a tree infrastructure of fibre optics at the LV level. This is because there is not such a strict requirement for reliability of communication in terms of an electrical grid. The redundancy of the power grid is typically higher (more reliability is needed) than required by communication networks. At the MV level, a simple looping of lines with a relatively large network extent (typically 12 to 16 elements in a ring) is sufficient. There will be a large number of connection points at the lower level of the network (LV) and therefore networking needs to be planned efficiently. Not all LV power cables will have fibre optics because, as mentioned above, the redundancy of the LV power network is significant.

Data

The existence of GIS data is assumed, the data which contains the network topology and basic attributes, in particular the type of point - node, type of link (LV ground cable, cable including HDPE tube or not, cable including optical cable or not), length of sections and their Renewal Index or cable age information.

Mathematical apparatus and computer processing

When designing a network, we cannot do without mathematical apparatus and computer processing. Many situations in mathematics, in computer science and in various practically motivated problems can be captured by a diagram consisting mainly of two things - a (finite) set of points and the connections between some pairs of points. The points in such a scheme are conventionally called vertices and the corresponding connecting lines are called edges. Also in our case, vertex and edge are the basic elements for describing the topology of the network. A network node (network element) represents a vertex, and a segment (optical cable route) represents a link between two nodes - an edge. The description of the network is possible using the set of vertices V and the set of two-point subsets of V (the set of edges E). The ordered pair (V, E) forms a graph G (an ordinary undirected graph as defined in [18]). In addition, there is often an evaluation of the edges by some metric M, e.g., length of a segment, cost of construction, age of the cable, etc.

It is therefore advantageous to apply graph theory as stated in [21]. It uses a graphical representation of the network and its description using matrices and algorithms to find paths through the graphs.

As far as computer processing is concerned, MATLAB is used for calculations, modelling and visualisation of designed optical infrastructure.

5.2 Finding the optimal topology

An important step for finding the physical topology of the network is to find the optimal path through the graph that meets the desired criteria. Using optimization, a subgraphs is extracted from the complete graph. Solving for the optimal topology at the transmission medium layer involves finding the minimum path through the evaluated graph. [21]

In terms of building optical networks, a spanning tree is the minimum possible topology for the physical interconnection of network nodes so that a communication between any pair of nodes can be implemented. A spanning tree is a continuous subgraph that connects all vertices of the original graph with its edges and at the same time itself does not contain any circle (closed path through the graph). [18] As mentioned in [21], a spanning tree does not provide the possibility to physically back up transmission paths. The Kruskal's algorithm or Jarník's algorithm, known also as Prim's algorithm, are used to find a minimum spanning tree (MST) of a graph. These algorithms are described in more detail in [18].

For backup, a circular topology is preferred, which in graph theory corresponds to the so-called Hamiltonian circle. It is a closed path passing through all nodes of the graph exactly once. This is essentially a solution to the so-called travelling salesman problem, mathematically expressing and generalising the problem of finding the shortest possible path passing through all given nodes on the map. However, when finding a path on the map, there is often a part of the path that must be traversed back and forth. This situation is undesirable for full physical backup, the routes must lead physically separated with sufficient distance. If the backup solution is to try to connect a particular subnet to two different points on the backbone, the solution is a Hamiltonian path. This is a continuous path that contains every vertex in the graph (i.e. traverses each vertex just once from the start node to the end node). [21][16]

In addition to this, it is good to note that for large networks, partitioning into hierarchical levels (higher/lower, primary/secondary level, etc.) is performed. In graph theory, this leads to a decomposition of the graph into subgraphs with their eventual linking through selected nodes of higher level networks. [21]

In general, we can use a minimization criterion based on the summation of all edges contained in the resulting graph or subgraph in each step of the algorithm as given in [21]:

$$W = \sum_{i=1}^{N} L(i)P(i)S(i), \tag{1}$$

where L stands for the edge length (in this case the length of a cable), P is the priority (typically a Renewal Index can be added, possibly weighted by some function), and S is a strategic factor that allows us to prioritise certain edges (e.g., taking into account the continuity of the graph being built). The importance of each factor can be adjusted by scaling (a range of min-max values, where 1 is a neutral value that does not affect the resulting metric).

The above formula is already a simplification of the problem. For a more advanced optimization, it would be more appropriate to start not from a metric that takes into account the length of the sections but the cost of the construction and to base it on the annual allocation of investment funds.

5.3 Getting the circular topology

In [21] several options and variants of circles for backup are presented. An elementary circle connected to the same network backbone point (orange) with partial use of the same route (Figure 5a) and an elementary circle connected to a single network backbone point (Figure 5b) are unsuitable from a reliability point of view - they are not resilient to failure of some (e.g., backbone) points. Circles connected to two different backbone points (Figure 5c) are ideal from a backup point of view.

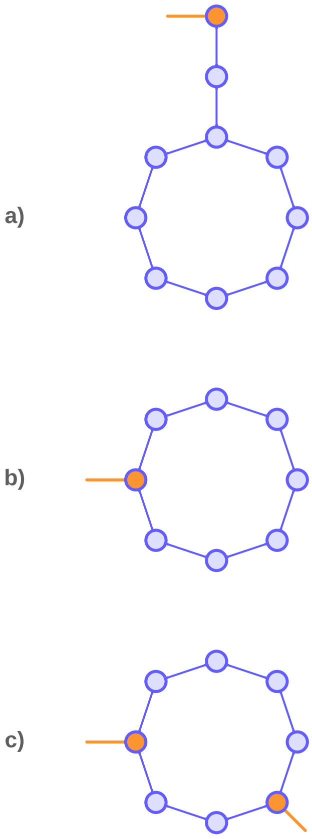

Figure 5: Circular topologies - backbone nodes (orange points), connection to backbone (orange lines), lower level connections (blue lines)

5.3.1 Hamiltonian cycle/path

One way to obtain a circular topology is to determine the optimal coverage of the power network with optical paths according to the algorithm for finding the Hamiltonian cycle or Hamiltonian path at the very beginning and then take into account this selected ”target solution” in the gradual construction of the network. As mentioned above, this is essentially a solution to the so-called travelling salesman problem, which is a difficult discrete optimization problem. The optimization version of the travelling salesman problem is one of the so-called NP-hard problems, i.e., in the general case it is not known how to find an exact solution for each input in reasonable time, or whether there can even be an algorithm that finds such a solution in time proportional to some power of the number of nodes. [16]

5.3.2 Spanning tree with added links

Given the large time complexity of the travelling salesman problem in the case of a large number of nodes in the graph, it is appropriate to consider the other possibility of obtaining a circular topology, as presented in [21], namely building a continuous network (graph's spanning tree as in Figure 6) and then only solve the addition of few links to the spanning tree to create network that is backed up. According to [21] this is done most efficiently by adding short links between two spanning trees with different root nodes as in Figure 7. In general, this may not be the most efficient approach (the number and length of links can be enormously large). However, given the nature of the initial topology (it is not a complete graph, but a circular redundant LV subnetwork built with power supply backup in mind), the inefficiency is unlikely to be that significant.

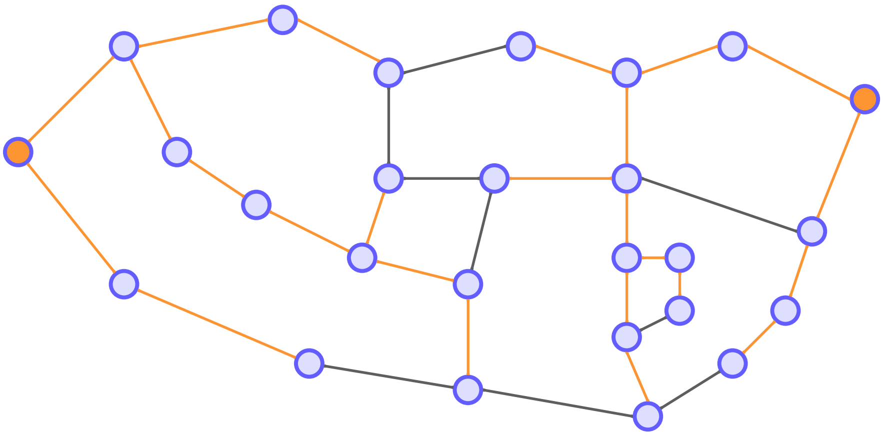

Figure 6: Example of network fully covered with optical connection (orange links) using 2 spanning trees from root nodes (orange nodes)

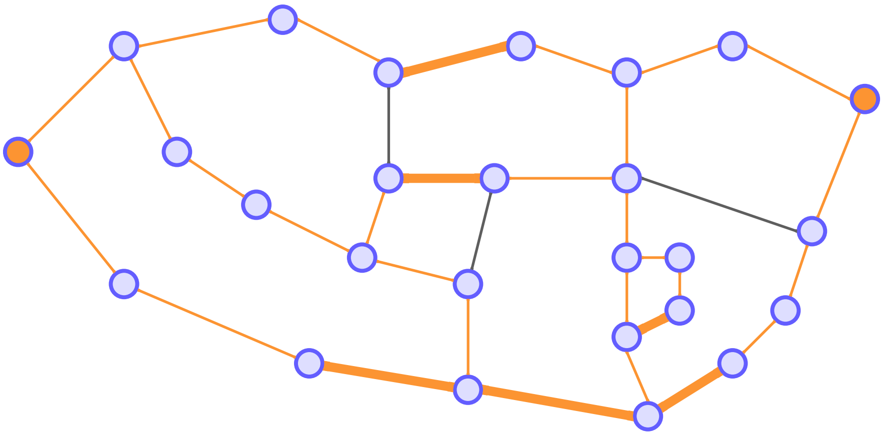

Figure 7: Example of network fully covered with optical connection (orange links) using 2 spanning trees with added links (bold orange links)

5.3.3 Edge removal method

Another possible approach to obtain the final solution of the backed up optical network is to take the complete graph of the power grid of a certain level as a starting point. Again, the circular redundant LV subnet built with regard to backup power supply will be used. We assume that communication backup will require less redundancy than the power network. The procedure will be such that we take the redundant edges of the power network, but so that each vertex is at least of degree 2 (i.e., at least 2 edges terminates in it). Thus, we will focus on edges that terminate in nodes that have degree 2 or more. If an edge connects two vertices where each has degree greater than 2, it can be removed (as shown in Figure 18). We first remove the edges with the highest weight (longest edges, edges with the highest costs...). In doing so, it is also necessary to take into account the power lines in parallel and replace them with a single edge.

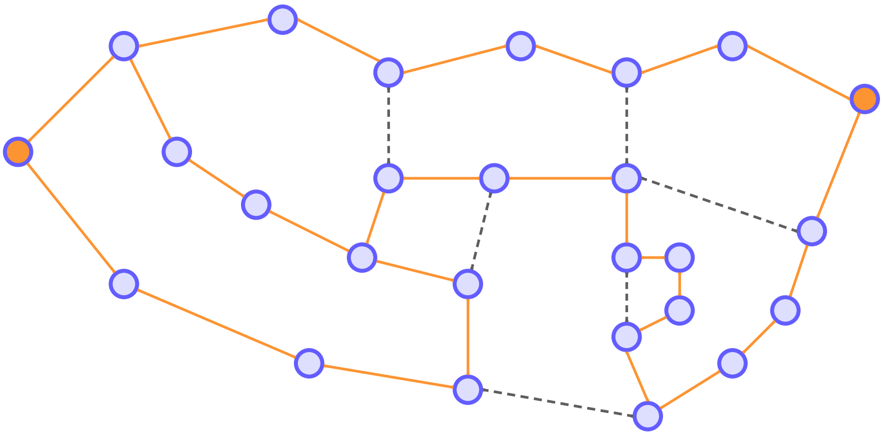

Figure 8: Graph after removing redundant edges - removed edges (dashed lines), edges left (orange edges)

5.3.4 Limitations in building a backed up optical network

[21] also lists the limitations of building a backed up optical network and it poses an important practical question about how many nodes should be connected in one continuous network (circular backed up subnetwork). It also states that we usually encounter the limitations of a given technology and its backup mechanisms, the overall capacity of the subnetwork, and the resulting required network availability (reliability).

The limiting factors and recommended properties for building circular network according to [21] are as follows:

- Preferences for connecting a circle at 2 different points to a higher hierarchical network.
- Limitation by the physical length of the section between 2 active elements (according to the type of optical interface 10, 30, 50, 90, 120 km) - it will practically not limit us at the MV or LV level.

- Dividing larger networks into subnetworks - a compromise between cost and feasibility (resulting reliability - the higher the amount of elements in the cascade, the lower the reliability, the longer the convergence time in case of failure - protection in a circle), i.e.
  - Limitation of the number of network elements in the cascade (consider maximum of 16 to 20 pieces),
  - Higher level hierarchies require greater robustness and reliability,
  - Lower level subnets - consider whether a single point to a higher level network is sufficient,
  - Number of optical ports on network elements at the points of contact of more circles - will mean a more expensive element (a common element on a circle requires exactly 2 optical line ports),
  - It also depends on the choice of the mechanism of interconnecting subnets and their backup - switching at L2, routing at L3.

These factors should be considered when tuning the resulting algorithms or applied in the final design stage.

Before the actual implementation, it is also necessary to check the parameters of the optical path connecting each pair of nodes, especially in terms of maximum bridging attenuation and path dispersion. In the backhaul and access network corresponding to the MV and LV level, the distances in the metropolitan network are typically up to 1 km between network nodes. Thus, control of the above parameters is not necessary, with a reserve range of typically 10 km of SM fibre interface at 1310 nm being sufficient. [21]

6 Optical network design in selected locations

Next, an optical network is designed for the needs of electricity distribution, based on the theoretical information discussed above, and the methods are applied to several power grid samples at the LV level.

6.1 Used software

MATLAB is used to design the telecommunication network. MATLAB version R2021b has been chosen for working with the data. It provides a list of functions for:

- creation of the graph itself on the basis of a list of vertices and edges - vertices and edges can be assigned names, weights, directions and other attributes, it is possible to create and work with both undirected and directed graphs and weighted graphs,
- analysis - determining the number of edges, vertices, components, locating vertices and edges, determining the degree of vertices, number and location of adjacent vertices or adjacent edges,
- editing - adding and removing edges and vertices, adding and changing their parameters, creating subgraphs,
- graph visualisation - label nodes and edges, highlight nodes/edges/paths, change edge line width/colour based on parameters, extract subgraph and more.

It also provides some basic algorithms from graph theory, e.g. for finding paths in a graph or finding a minimum spanning tree of a graph, etc.

6.2 GIS data

The data provided by PREdi comes from the Geographic Information System (GIS). GIS systems link positional data with other data sources describing the properties of the objects being mapped. The data consists of two components - spatial and attribute data. The spatial component can be expressed as a geometric feature or its database record (typically coordinates or a link to another spatial feature). The attribute component of this data contains information that is used to describe the spatial component, for example, it contains information about the location and shape of the object, or a description of the relationships between the spatial components.

PREdi provided us with samples of several parts of their LV network, specifically parts of the districts Chodov, Nové Město and Vinohrady in the capital city of Prague, Czech Republic. The samples cover areas with family houses and panel buildings (Chodov) or built-up areas in the form of a closed block structure (Nové Město, Vinohrady). The samples are in the form of file with network topology (nodes, branches) and file with attributes to the individual network sections - both tables in xlsx format.

In the case of the table containing the topology, mainly the two-dimensional coordinates of nodes for link starts and ends were used to create a graph of the given sample network (nodes = vertices, links = edges). The coordinate system used is S-JTSK (Křovák). The lengths of the individual links were used to weight the edges in the graph. The IDs of the given nodes were used to identify the nodes of the LV network (TS - secondary substation, RIS - distribution point, SP - fuse cabinet, NNS - LV connector). Each row of the table corresponds to one link between two nodes.

The attribute table that was used for the purpose of this work contains information for the links listed in the topology table. Each row of the attribute table contains information for one link in the table containing the topology.

The table contains attributes such as ID, length and cross-section of the installed cable, type of installed cable (CYKY, AYKY or AYKY-OT, where OT indicates that HDPE tube is installed in the cable sleeve for possible fibre optic cable insertion), type of section (cable section, cable section in tunnel), ownership and owner (the vast majority of sections (cables) is owned by PREdi), date of installation, the weighted price (at the moment this data is not used within PREdi), the age of the cable (routing according to age, -1 = newest cable, do not route this section as part of the renewal) and information whether the power cable allows the installation of optics (can be identified by the abbreviation OT in the designation of the type of installed cable, where OT = optical tube) and whether optics is already installed in such cable. If optics is already installed in this cable (section), then the given parameter is set to "YES" in the attribute table. Of course, older cables do not allow this, so the parameter will be "NO" for their entire lifetime.

The last mentioned parameter was not used in the selection of the edges for the optical network design described below - when designing the optical network we did not take into account that some LV cables in the provided sample already contain optical fibres or tubes for blowing optics. However, it was later evaluated how many such cables were selected by the implemented algorithms for the purpose of implementing the communication infrastructure.

Based on the above described tables provided by PREdi, a weighted non-oriented graph was constructed for each data sample for the purpose of designing the optical communication network. The graphs generated in this way may contain multiple components or discontinuities due to the fact that the samples do not contain follow-up data (Figure 9). If necessary, this can be solved by a larger sample that contains this data. However, a larger area would not be beneficial because there will be discontinuities at the boundary of any large sample. Thus, in further processing, these small discrete components at the edge of the samples were not considered and were removed.

Then, multiple edges and self-loops, which are redundant for the optical network wiring, were removed from the graphs. In the case of multiple edges between two nodes, one link was selected based on the preferred weight (e.g., in terms of length, it was the edge with the shortest length which corresponds to the minimum weight). Also LV connector nodes were removed from the graphs and the links connected by connectors were replaced with single direct connections. After these modifications the previously described methods from chapter 5 were applied to the 3 created graphs (one graph per district data sample).

Figure 9: Chodov - Multiple separate components distinguished by different colours

6.3 Sample data analysis

This section describes the properties of the 3 data samples from different locations in Prague provided by PREdi. Each sample examined below represents the biggest connected component of data sample for the particular district.

6.3.1 Chodov data sample

In total, the sample consists of 782 links (edges) that form connections between 711 nodes of which 16 secondary substations, 123 distribution points, 515 fuse cabinets, 52 LV connectors and 5 ”unnamed” nodes. The ”unnamed” nodes represent virtual nodes. Generally, names are assigned to nodes automatically from the lines, unnamed nodes are mostly auxiliary points that cannot be assigned to a physically existing point. These are points created by the person entering the data into the GIS. Typically, these are cable sections that are not connected by any physical point (unlike for example LV connector), it means an uninterrupted cable. Nevertheless, it was necessary to connect the cables via this auxiliary (virtual) point during the plotting process. Since the number of these points is negligible in this case, they are treated as LV connectors when designing an optical network, without affecting the overall result.

By further analysis based on the available data in the attribute table, we can state that the sample contains 610 edges with HDPE tube (78% of all edges) covering 566 nodes (80% of all nodes) and 26 edges (3% of all edges) already including optical cable and covering 27 nodes which are connected to the optical network (4% of all nodes in the sample). Altogether, there are 37 km of links (cables), of which approximately 26 km (69%) contain an HDPE tube for blowing optical fibre and 1,5 km (less than 4%) of cables with already installed optical cable.

After removing multiple edges, LV connector points, self-loops and small components at the edge of the sample, we obtained a graph (Figure 10) with 662 nodes, 729 edges (36,32 km) of which 24 edges (1,29 km) with optics in place and 583 edges (25,08 km) with HDPE tubing installed but still empty.

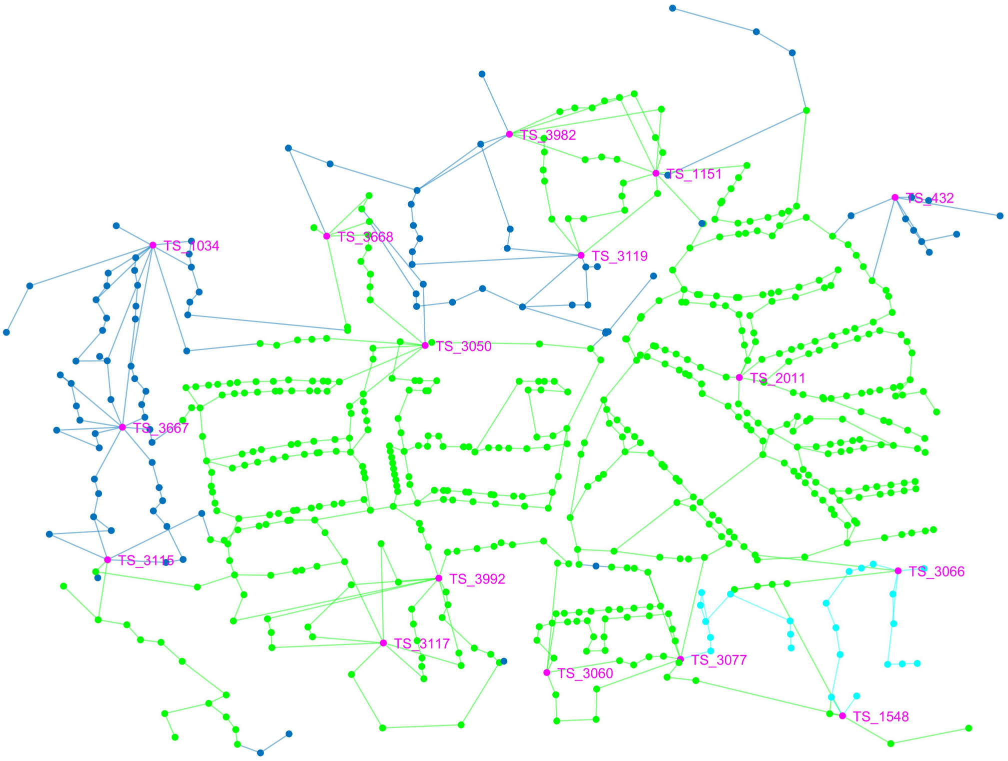

Figure 10: Chodov - Optical cable (cayen) and empty HDPE tube (green) coverage with secondary substations highlighted (magenta TS nodes)

6.3.2 Nové Město data sample

In total, this sample consists of 790 links (edges) that form connections between 665 nodes of which 28 secondary substations, 133 distribution points, 309 fuse cabinets, 186 LV connectors and 9 virtual nodes. Since the number of the virtual points is negligible for this district's data sample, they are treated as LV connectors also in this case.

The sample contains 6 edges with HDPE tube (less than 1% of all edges) covering 6 nodes (also less than 1% of all nodes). There are no edges with already installed optical cable. Altogether, there are 32 km of links (cables), of which only around 220 m contain an HDPE tube for blowing optical fibre.

After removing multiple edges, LV connector points, self-loops and small components at the edge of the sample, we obtained a graph (Figure 11) with 482 nodes, 588 edges (30 km) of which 2 edges (88 m) with HDPE tubing installed but still empty.

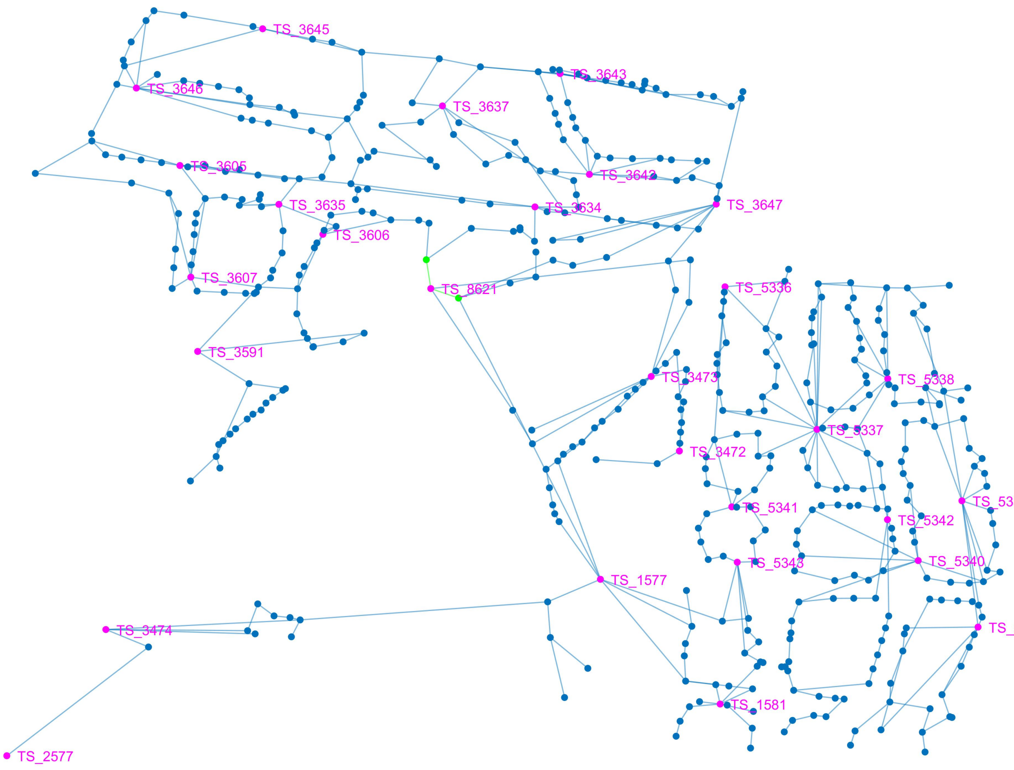

Figure 11: Nové Město - Empty HDPE tube (green) coverage with secondary substations highlighted (magenta TS nodes)

6.3.3 Vinohrady data sample

In total, the Vinohrady sample consists of 439 links (edges) that form connections between 407 nodes of which 17 secondary substations, 60 distribution points, 280 fuse cabinets, 36 LV connectors and 14 virtual nodes. Also in this case the virtual nodes are treated as LV connectors.

The sample contains 7 edges with HDPE tube (around 1,5% of all edges) covering 9 nodes (2% of all nodes). There are no edges with already installed optical cable. Altogether, there are 14 km of links (cables), of which only around 240 m contain an HDPE tube for blowing optical fibre.

After further modifications (removing multiple edges, LV connector points, self-loops, small components) we obtained a graph (Figure 12) with 361 nodes, 391 edges (13,77 km) of which 6 edges (180 m) with HDPE tubing installed but still empty.

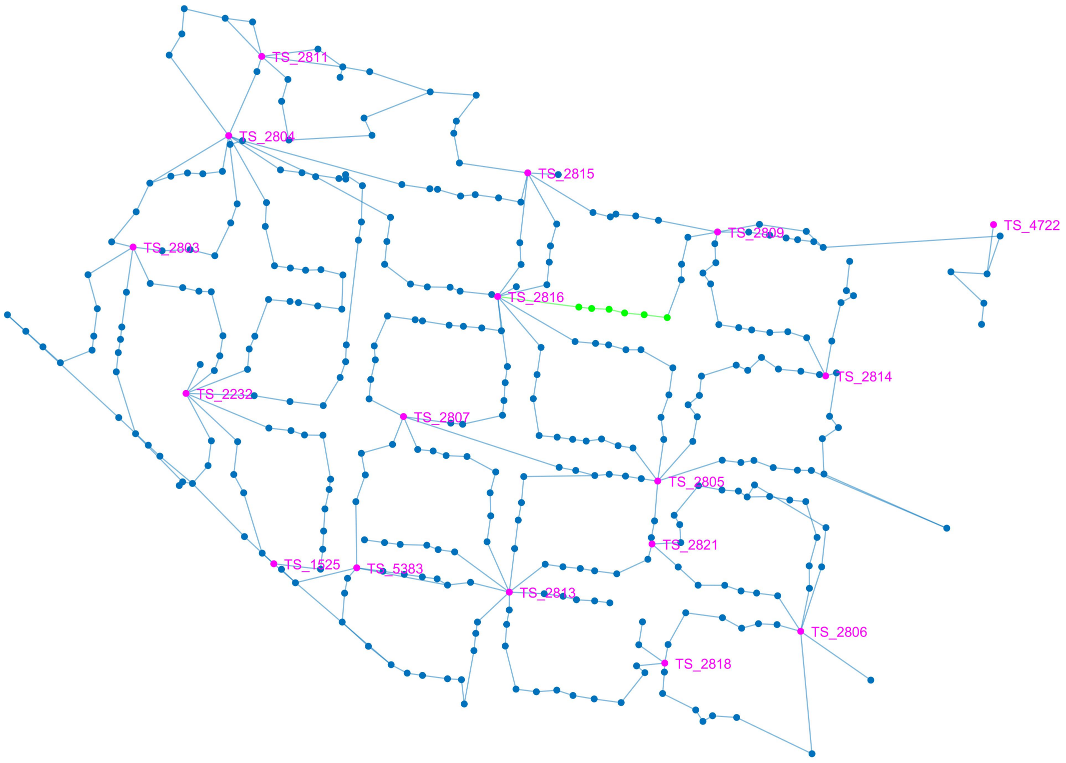

Figure 12: Vinohrady - Empty HDPE tube (green) coverage with secondary substations highlighted (magenta TS nodes)

6.4 Application of the methodology to the selected site

The individual algorithms used to select edges in the LV level distribution network graph are described below, along with the resulting graphs for each procedure. For clarity, only the graphs and resulting selections based on the Chodov district's data sample are used in this chapter to illustrate each procedure. Intermediate results and resulting plots for the other two samples are presented in Appendix.

6.4.1 Minimum spanning tree

For connected graphs, a spanning tree is a subgraph that connects every node in the graph, but contains no cycles. There can be many spanning trees for any given graph. By assigning a weight to each edge, the different spanning trees are assigned a number for the total weight of their edges. The minimum spanning tree (MST) is then the spanning tree whose edges have the least total weight.[18]

For the purpose of finding the minimum spanning tree, 'minspantree', the MATLAB built-in function, was used. By setting the parameters of the function, we can choose one of the algorithms for finding the minimum spanning tree – Prim's or Kruskal's algorithm. Prim's algorithm starts at the root node (the default root node is the one with index eaqual to 1) and adds edges to the tree while traversing the graph. Kruskal's algorithm sorts all of the edges by weight, and then adds them to the tree if they do not create a cycle. [18] describes these algorithms in more details.

Kruskal's algorithm

Kruskal's algorithm finds a subset of a graph G such that:

- It forms a tree with every vertex in it.
- The sum of the weights is the minimum among all the spanning trees that can be formed from this graph.

The steps for implementing Kruskal's algorithm are:

1. Sort all edges in G in non-decreasing order of their weight.
2. Pick the edge with the lowest weight. Check if it forms a cycle with the spanning tree formed so far. If cycle is not formed, include this edge. Else, discard it.
3. Repeat step 2. until all vertices are reached (until there are (V-1) edges in the spanning tree where V is the number of vertices in the given graph G).

Prim's algorithm

Prim's algorithm is yet another algorithm to find the minimum spanning the tree of a graph. In contrast to Kruskal's algorithm that starts with graph edges, Prim's algorithm starts with a vertex. We start with one vertex and keep on adding edges with the least weight until all the vertices are covered. [18]

The steps for implementing Prim's algorithm are:

1. Start at any node in the graph.
2. Mark the starting node as reached.

3. Mark all the other nodes in the graph as unreached. (Right now, the minimum spanning tree consists of the starting node. The minimum spanning tree is expanded with the procedure given below.)
4. Find an edge e with minimum cost in the graph that connects a reached node x to an unreached node y.
5. Add the edge e found in the previous step to the minimum spanning tree.
6. Mark the unreached node y as reached.
7. Repeat the steps 4 - 6 until all nodes in the graph have become reached.

There may be several minimum spanning trees of the same weight, in particular, if all the edge weights of a given graph are the same, then every spanning tree of that graph is minimum. In this case, both algorithms found the same minimum spanning tree of a given weighted undirectional graph. The found minimum spanning tree for Chodov district's data sample is shown in Figure 13.

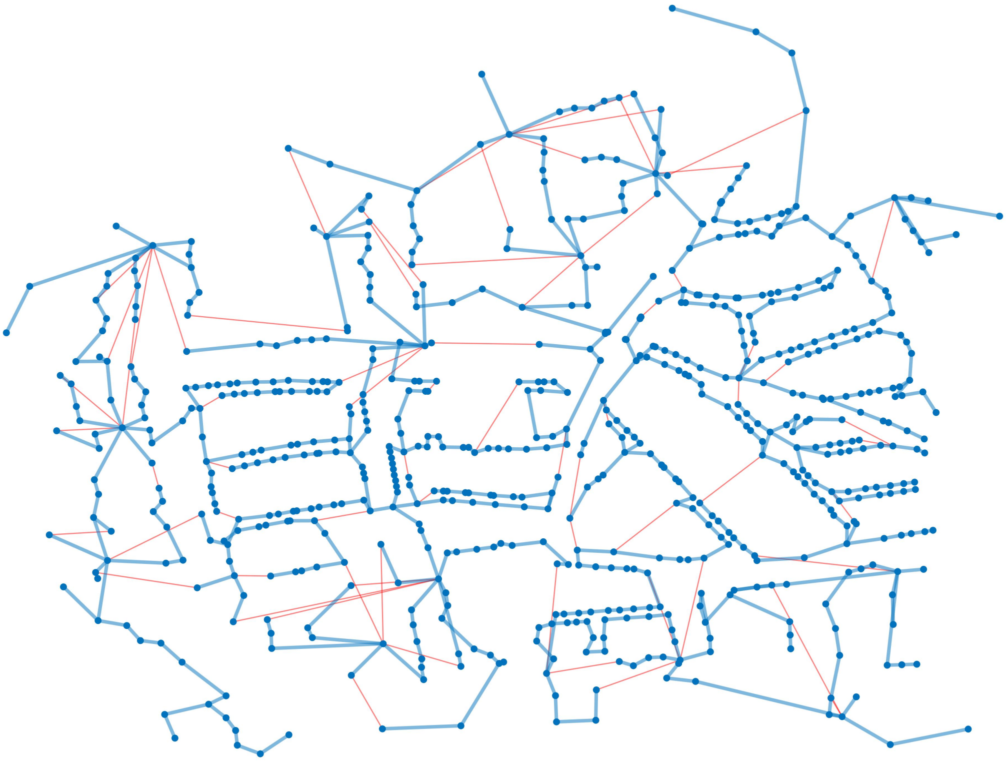

Figure 13: Chodov - Minimum spanning tree (blue) and not chosen links (red)

6.4.2 Spanning trees with added links

The design and functionality of this algorithm relies on a certain structure of the distribution network and the location of the secondary substations. Based on this network design, the sample network was divided into two parts, which were further processed.

In order to split the graph into two parts, to find two minimum spanning trees and add connecting links, secondary substations were first identified in the graph to represent backbone network nodes (it was assumed that they are either already connected or soon to be connected to the optical network). Then, the shortest paths between each pair of secondary substations were found. We assumed that there would not be that many secondary substations in the sample and thus not that many paths to find. Indeed, the secondary substations were representing just around 2% of all nodes in the Chodov data sample (around 4% of nodes in the other two data samples provided). From these nodes, pair of such backbone nodes was selected for which the distance between the nodes was the greatest (Figure 14). The distance considered here is the found shortest path between the two backbone nodes in the evaluated graph, where the edges are weighted by the length of the segments given in the topology table.

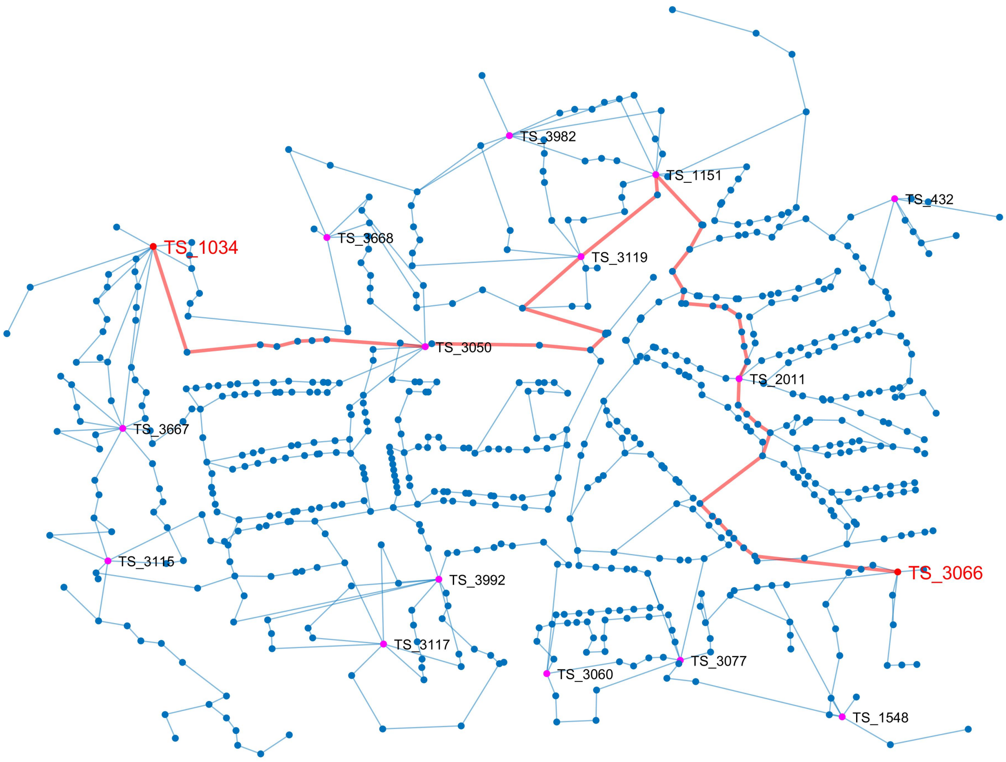

Figure 14: Chodov - Chosen root nodes (red) and shortest path between them (also red)

Based on the coordinates of the selected pair of backbone nodes, the vertical or horizontal boundary intersecting the graph in terms of the node coordinates approximately in the centre was determined. This divides the vertices in the graph into two roughly equally sized sets of nodes, depending on whether the coordinates of the given nodes are to the left or to the right (resp. above or below) this imaginary line. The two sets thus determined contain one of the selected backbone nodes (red nodes in Figure 15).

Figure 15: Chodov - Two subsets of nodes (light blue and green) with links between them (red) divided by borderline (dark blue)

Hence, two subgraphs were obtained from one graph on which minimum spanning trees were found by Prim's algorithm as depicted in Figure 16. In both cases, the two previously selected backbone nodes were used as the root nodes in given subgraphs.

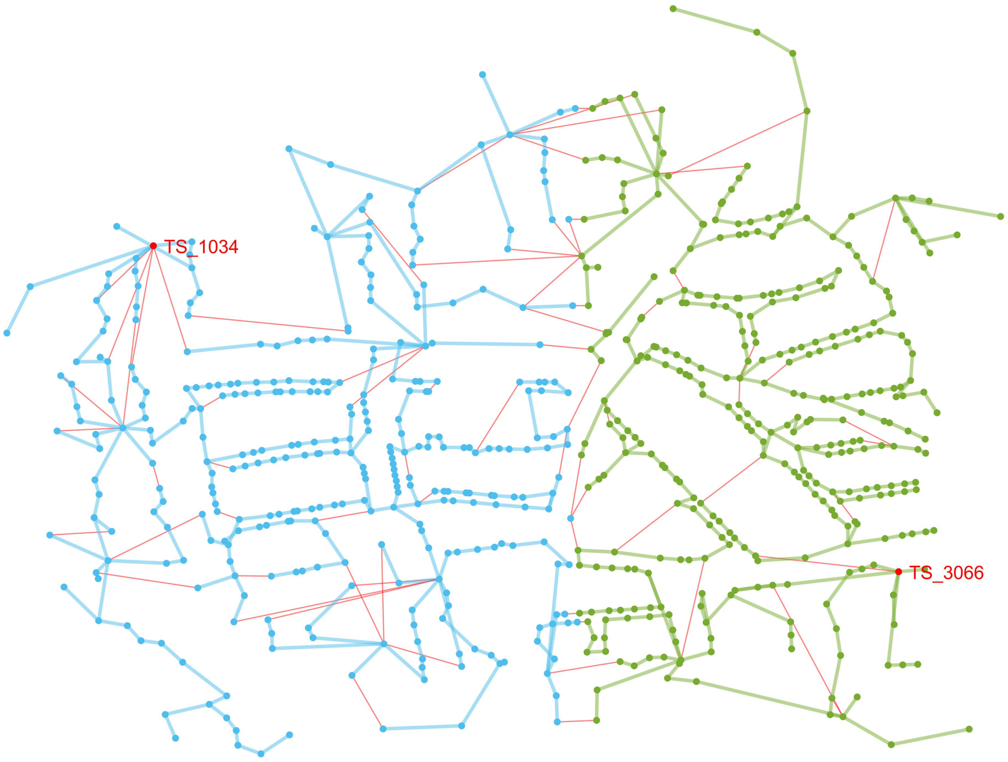

Figure 16: Chodov - Two spanning trees (green and blue) and potential conjunctions (red)

Subsequently, these two subgraphs were augmented with conjunctions. The conjunctions were added wherever the degree was less than 2. The conjunctions were added one at a time and the edge with the smallest weight was always added first. At each step, the change of node degrees was checked and the set of potential conjunctions was reduced if necessary. Figure 17 shows the resulting subgraph of chosen edges (blue) along with the edges that were not chosen by the algorithm (red).

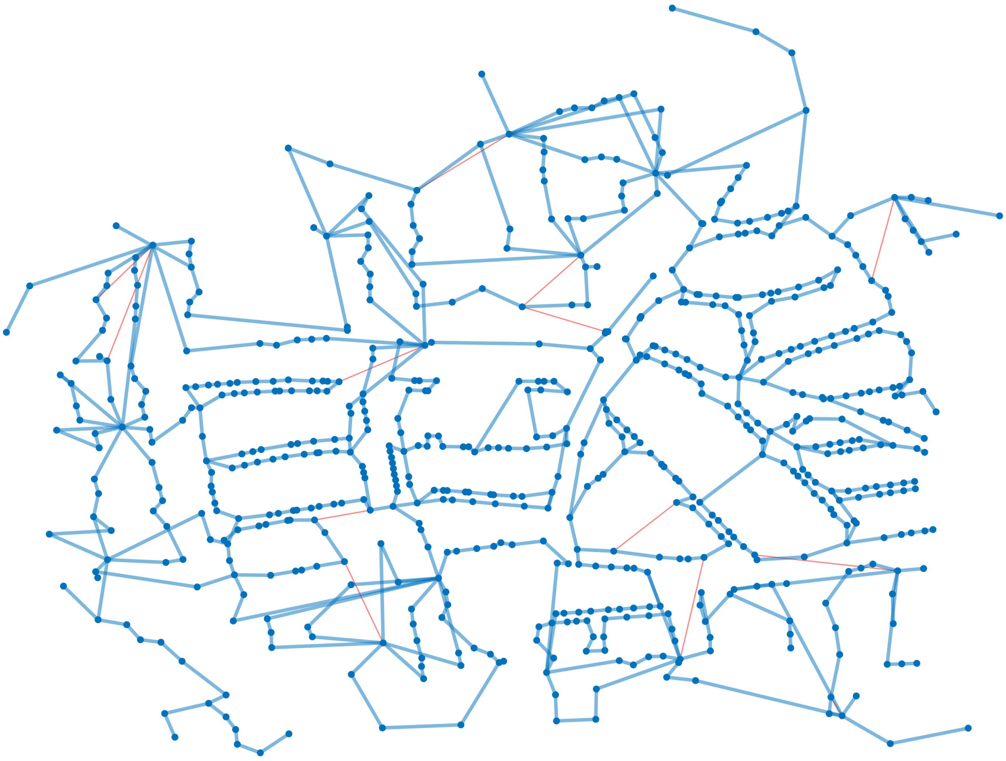

Figure 17: Chodov - Spanning trees with added links (blue) with edges that were not chosen (red)

The pseudocode for the method described above is on the following page.

Pseudocode

```
1. Make graph G based on dataset provided, use lengths of the cables as weights of edges.
2. Get all pairs P of secondary substations (nodes marked as 'TS') in graph G.
3. Find the shortest path for each pair in P.
4. Pick pair p from P with the longest shortest path (= get the pair of secondary substations with the greatest distance between them).
5. Depending on the position of p set a vertical (horizontal) borderline based on coordinates of nodes in the middle of the graph G (set x (y) coordinate as median of all x (y) coordinates).
6. Divide the nodes of G into two subsets – nodes on the left side of (above) the borderline and nodes on the right side of (under) the borderline (each subset includes one secondary substation from p).
7. Make 2 subgraphs - one for each subset of nodes.
8. Use Prim's algorithm to find 2 minimum spanning trees – one tree for each subgraph (use secondary substations from p as root nodes).
9. Merge 2 trees to make one bigger subgraph G_trees.
10. Create subgraph G_left by removing edges of G_trees from graph G.
11. While there are still edges in G_left (there are still some edges to add):
    • N = get nodes with degree 0 or 1 in G_trees = nodes where links may be added.
    • Get the "old" degree in G of nodes from previous step.
    • If degree in G == degree in G_trees for any node in N then remove such node from N (do not consider such nodes for added links).
    • Get edges in G_left adjacent to the nodes N = edges E that may be added to G_trees.
    • Pick edge with minimum weight from the set of edges E from previous step = edge e to be added to G_trees (in case of more minimums pick any of them).
    • Add e to G_trees.
    • Remove e from E.
    • Remove all edges that are not in E from G_left.
12. G_trees = result.
```

6.4.3 Edge removal method

In this case, all edges that could be removed were first identified according to the methodology described in 5.3.3 i.e. if an edge was connecting two vertices where each had degree greater than 2, it could be removed. Such edges were sorted according to their weights into a list of edges to be removed. At each step, the edge with the largest weight was removed and the degrees of the vertices between which the edge formed a connection were reduced. If the degree of any of these vertices dropped below 3, the edges belonging to that vertex were eliminated from the list of edges that could be removed from the graph. At each step, before removing a selected edge from the graph, a check was performed to ensure that removing the edge would not break the connectivity of the graph. In case the graph would break into two separate components after removing the selected edge, this edge was kept in the graph and was excluded from the list of edges that could be removed. These steps were repeated until the list of edges to remove was empty. The pseudocode for the Edge removal method is given below.

Pseudocode

```
1. Make graph G based on dataset provided, use lengths of the cables as weights of edges.
2. E = find all edges connecting nodes with degree greater than 2 in G.
3. While there are still edges in E:
    • e = pick the edge with the largest weight in E.
    • Check whether e can be removed or not:
        ◦ If G without e has one connected component:
            - Remove e from G.
            - Remove edges adjacent to nodes with degree that has dropped below 3 (due to
              removing e from G) from E.
        ◦ Else keep e in G and remove it from E.
4. G = result.
```

The resulting subgraph of chosen edges for Chodov district data sample is highlighted in blue in Figure 18. Removed edges are highlighted in red.

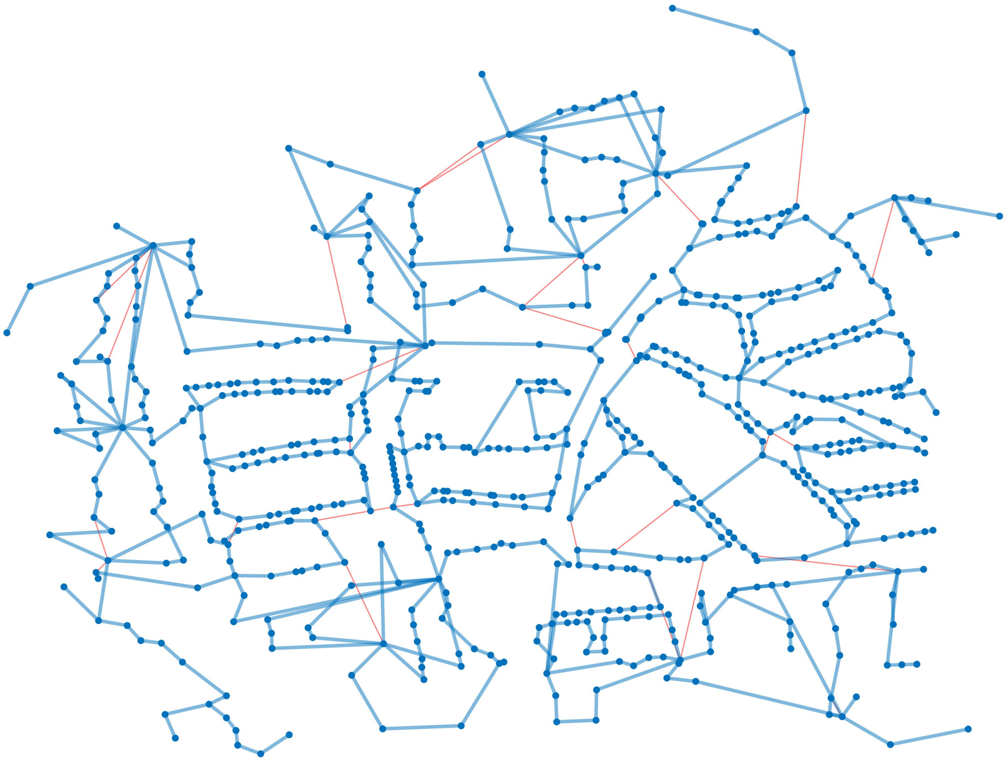

Figure 18: Chodov - Edge removal method resulting graph (blue) with edges that were not chosen (red)

6.4.4 Hamiltonian cycle/path

As mentioned above, finding a Hamiltonian cycle/path is an NP-hard problem. In this case, the sample distribution networks are large (hundreds of nodes). Simple algorithms such as looking for permutations are not applicable. Other algorithms may solve the problem of a high number of nodes, but they have to be applied mostly on dense or even complete graphs with a lot of connections where it is possible to find a Hamiltonian cycle/path. The structure of the distribution network (in all three data sample cases) is such that it would be necessary to go through certain nodes (highlighted in Figure 19 for Chodov sample) multiple times thus it would not be a Hamiltonian cycle/path. It is not possible to find a Hamiltonian cycle/path in the sample of the LV network provided without adding new edges to the graph (that would mean adding new cables where they are not installed yet which is not an option here).

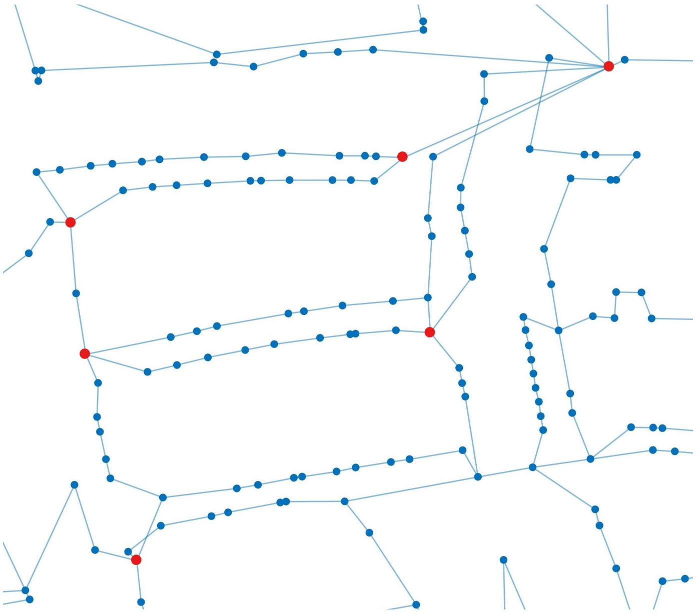

Figure 19: Chodov - Part of the sample network with nodes that would have to be visited multiple times on the way through every node highlighted (red)

Thus, finding the optimal coverage of the power network with optical paths according to the Hamiltonian cycle or Hamiltonian path algorithm right at the beginning was not considered in this case and we further tried to cover the given sample with circular subnetworks.

Circular subnetworks

First, we assumed the longest (in terms of number of nodes) cycle found that passed through all the secondary substations in case of Chodov sample (around half of secondary stations for Nové Město sample and almost all - except one - secondary substations for Vinohrady sample). The MATLAB built-in function 'allcycles' was used to search for cycles. Given the sample size, it was possible to find cycles of 280 nodes in a reasonable time in case of Chodov district data sample (cycles of 100 nodes for Nové Město sample, cycles of 150 nodes in case of Vinohrady sample). From these, the cycle passing through the most secondary substations with the least weight was selected (Figure 20). This cycle was taken into account in the successive network construction and additional cycles were found on the remaining edges (Figure 21) in the graph and included in the final solution.

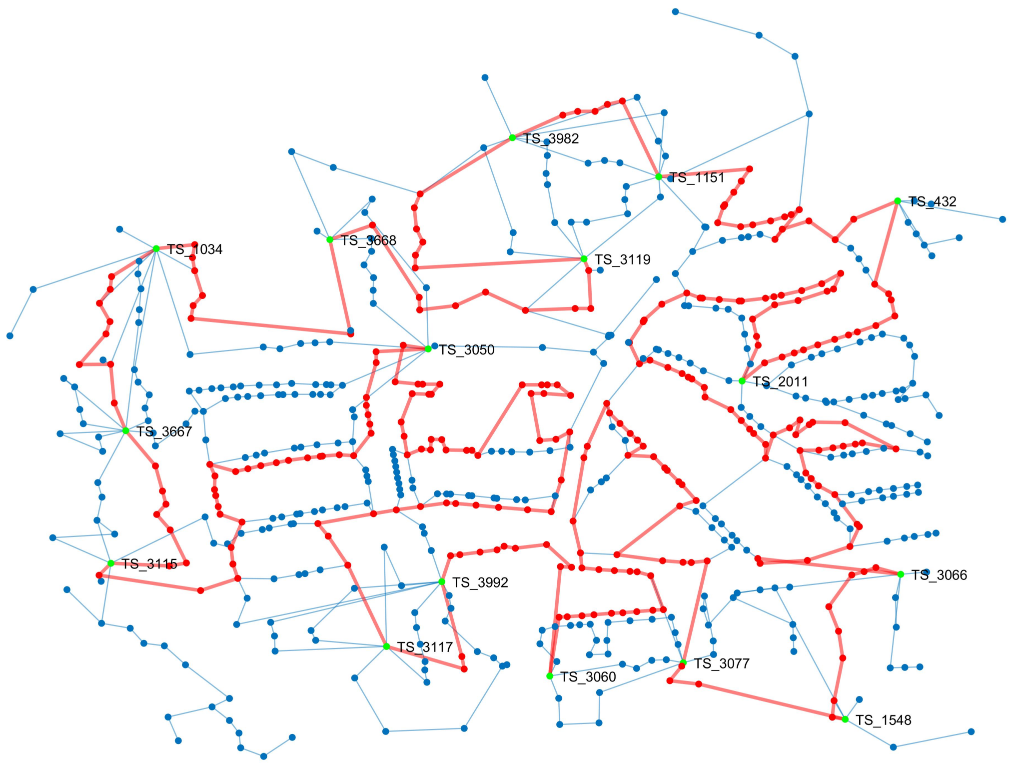

Figure 20: Chodov - Cycle (red edges) of 280 nodes passing through all secondary substations (green nodes)

Figure 21: Chodov - Edges left (blue) after removing the (red) edges of cycle highlighted in Figure 20

All cycles that were picked are highlighted in Figure 22. The figure shows that these cycles do not cover all the nodes in the sample.

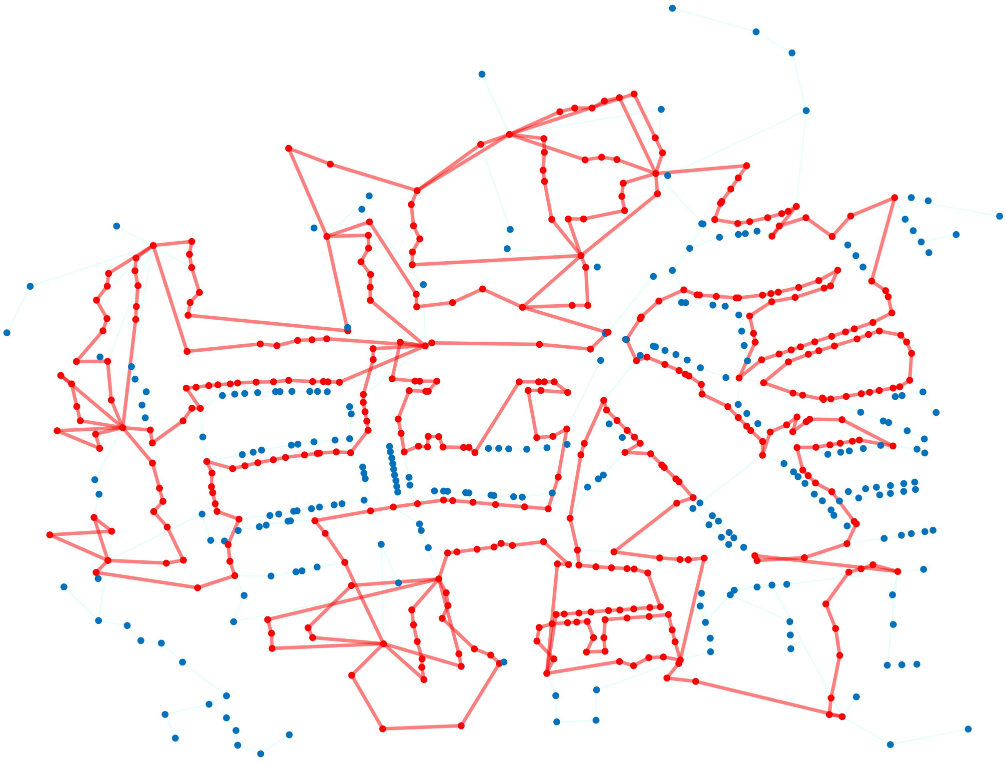

Figure 22: Chodov - All cycles picked (red) and remaining nodes to connect (blue)

The nodes that were not covered by these cycles were then connected to the cycles using the remaining edges with the smallest possible weights. The individual components of the resulting graph were connected together the same way which resulted in the final graph shown in Figure 23.

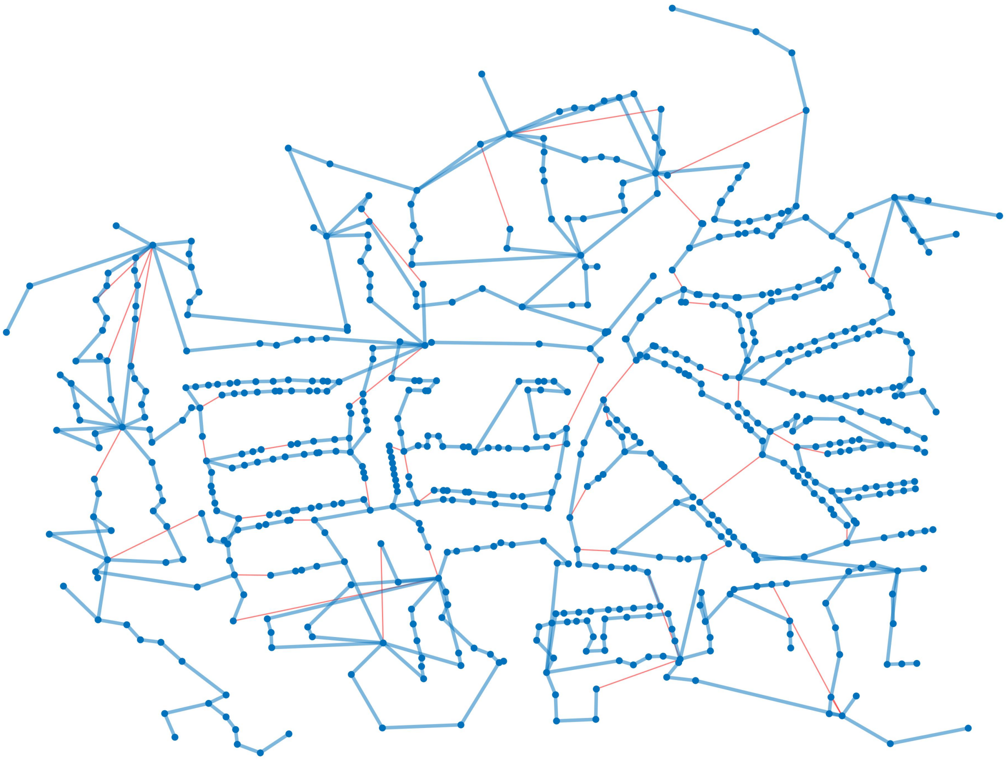

Figure 23: Chodov - Circular subnetworks result - chosen (blue) and not chosen (red) edges

Pseudocode for the method described above is given on the following page.

Pseudocode

```
1. Make graph G based on dataset provided, use lengths of the cables as weights of edges.
2. G_left = G.
3. Set length L = 280 nodes (the longest achievable cycle found in reasonable time).
4. Find set of 100 cycles C of length L in G.
5. For each cycle in C find number of secondary substations in this cycle.
6. Pick cycles with maximum number of secondary substations from C.
7. Pick cycle c with the lowest weight from cycles in previous step.
8. Remove edges of c from G_left.
9. While there are still cycles in G_left:
    • Obtain all cycles C_all in G_left.
    • Pick longest cycle with minimum weight c from C_all.
    • Remove edges of c from previous step from G_left.
10. G_new = remove edges of G_left from G.
11. While number of connected components of G_new > 1:
    • Identify the largest connected component in G_new.
    • Find edges in G_left connecting nodes of the biggest component of G_new and remove them from G_left.
    • Get edge e with the lowest weight in G_left.
    • Remove e from G_left.
    • Add e to G_new.
12. G_new = result.
```

Secondary substations cycle

In the case of finding a cycle passing through all the secondary substations as described above and connecting the nodes that were not covered by this cycle to it using the remaining edges with the smallest possible weights (skipping finding circular subnets - step 9 from pseudocode above), the resulting graph is shown in Figure 24.

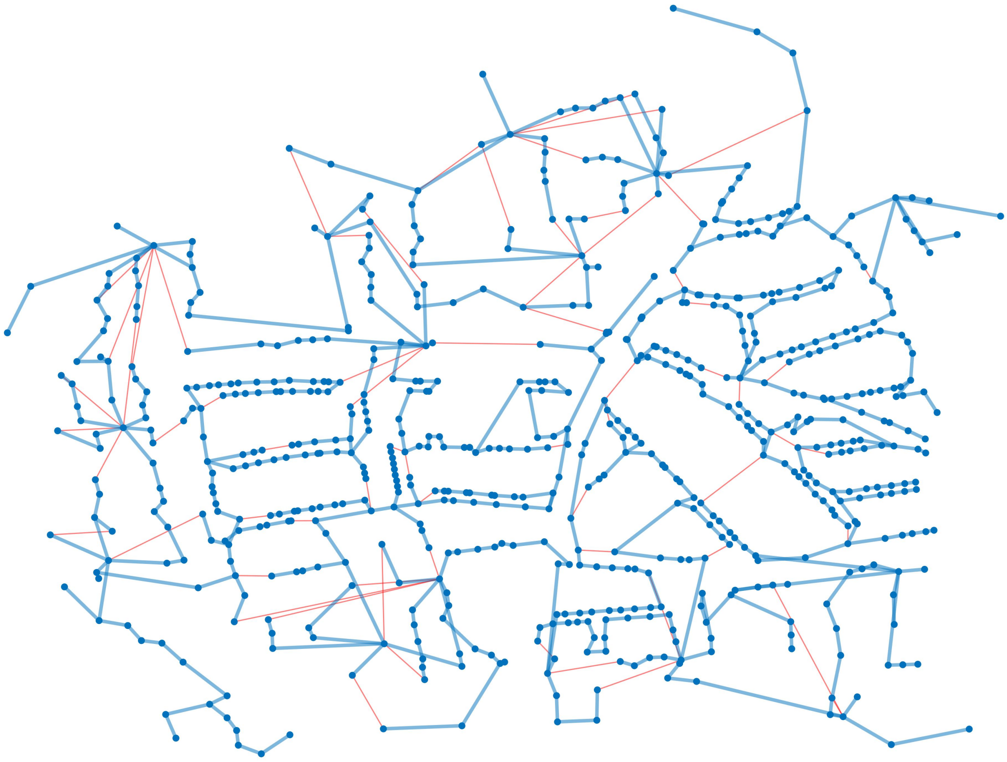

Figure 24: Chodov - All secondary substations cycle result - chosen (blue) and not chosen (red) edges

6.5 Other methodologies

All the methods described so far aim at a resulting fully interconnected network at LV level with varying degrees of redundancy. In addition to these methods, further procedures were applied to the samples. These do not necessarily aim at interconnecting all points at the LV level or direct connection of all points to the optical network.

In the first of these procedures, the interconnection of secondary substations at the MV level of the distribution network is assumed. The second procedure assumes direct connection of secondary substation nodes to the optical network at the MV level and use of another communication technology (BPL) in combination with the optical network at the LV level.

6.5.1 Secondary substations subnetworks

This method examines how coverage changes when the network at LV level is split into multiple subnetworks using secondary substations interconnection at the MV level. The starting points for this method are thus the secondary substation nodes. Additional nodes are gradually connected to these nodes. The network grows from the secondary substations and nodes are gradually added to the resulting graph until all of them are directly connected to the optical network. Of course, as in the previous methods, edges with the smallest possible weight (length) are preferred in the selection process. The pseudocode for the Secondary substations subnetworks method is given below.

Pseudocode

```
1. Make graph G based on dataset provided, use lengths of the cables as weights of edges.
2. Create subgraph G_new by removing all edges from graph G – get a graph with no edges but with all nodes from G.
3. Mark all nodes as not visited.
4. Set initial nodes N_init = all secondary substations.
5. Mark initial nodes N_init as visited.
6. While there are still nodes to visit in G_new:
    • Find all outgoing edges E_out from nodes N_init in G and the successor nodes Nb (neighbors) that are connected to N_init by edges E_out.
    • Remove duplicates in set of successor nodes Nb along with the edges in E_out connecting them to N_init and keep the connection in E_out for node in Nb with the lowest weight w i.e. if N_init nodes have the same neighbours (there are duplicates in Nb) keep the edge in E_out with the lowest weight w and remove the rest of the connecting edges from E_out.
    • Remove nodes from Nb and adjacent edges in E_out if those successor nodes in Nb have already been visited.
    • Mark nodes in Nb as visited.
    • Add edges E_out to G_new.
    • Set N_init = Nb.
7. G_new = result.
```

The resulting subgraph of chosen edges for Chodov district data sample is highlighted in Figure 25.

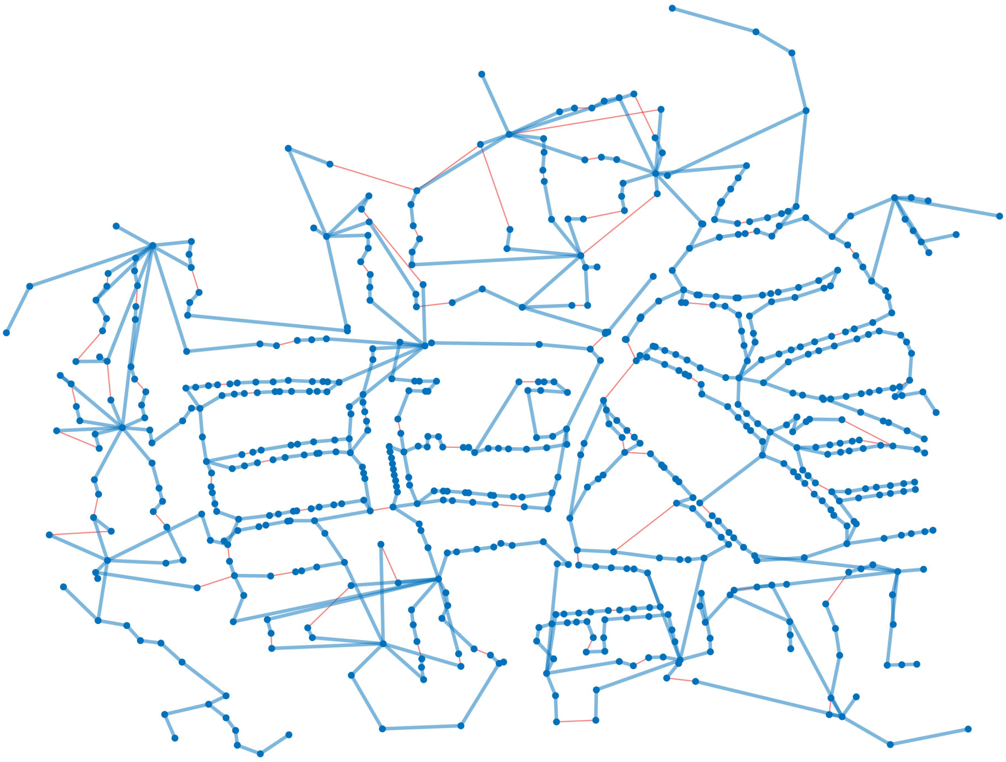

Figure 25: Chodov - Secondary substations subnetworks result - chosen (blue) and not chosen (red) edges

Chosen edges and nodes are highlighted in different colours depending on their belonging to a given secondary substation subnetwork in Figure 26.

Figure 26: Chodov - Secondary substations subnetworks highlighted in different colours

This procedure does not aim to interconnect all nodes at the LV level therefore it creates separate islands at this level - each secondary substation has its own seperate subnetwork at the LV level and the secondary substations are primarily optically connected at the MV level.

6.5.2 BPL and optical network combination

This approach is based on the idea that every third house/entrance/station is directly connected to the fibre network. The intermediate points will be omitted and connected to the optical network indirectly via another technology. The BPL technology considered in this case is serving other (both left and right) entrances (houses/stations) via power cables.

Due to the structure of the sample network at the LV level, it is not possible to simply omit points in the graph and connect every third house/entrance, as the graph contains sections of points connected in series. Thus, a different approach was chosen.

Again, the connection of secondary substations at the MV level of the network is assumed and the considered range of the complementary technology is determined (BPL has a range of the order of hundreds of meters - a value of 200 m was used for the simulations). Next, the distribution points are optically connected to their nearest secondary substation or other nearest directly optically connected point by the shortest path as depicted in Figure 27.

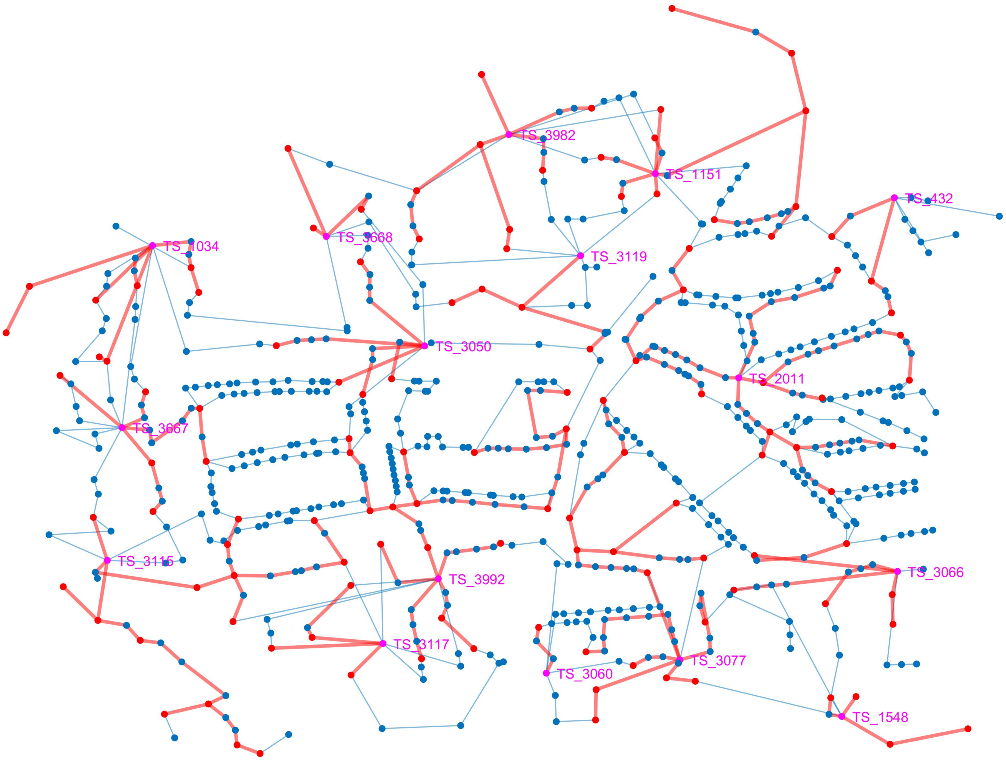

Figure 27: Chodov - Distribution points (red nodes) directly connected with the optical connection (shortest paths highlighted in red) to the nearest secondary substation (magenta nodes)

This is followed by checking the nodes that are not directly connected to the optical network (nodes different from the secondary substations, distribution points and different from nodes that lie on the selected shortest paths from distribution points to secondary substations) - if these points are not within the BPL range (further than 200 m from the nearest node directly connected to the optical network), optical links are added until all such nodes are at least within the BPL range (Figure 28).

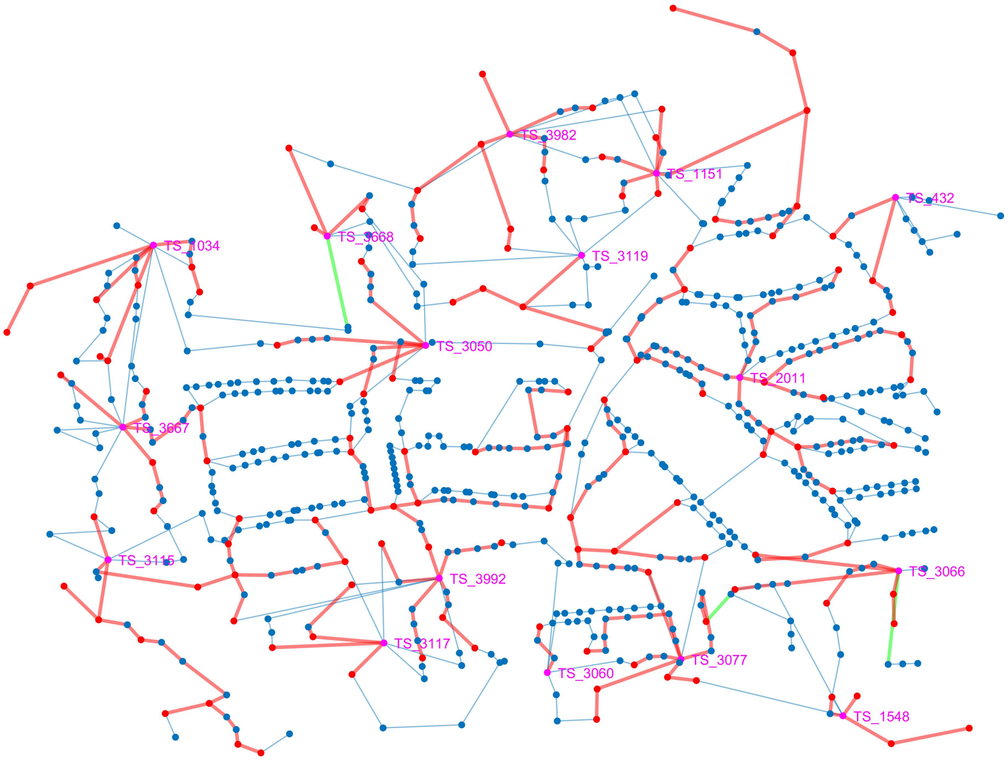

Figure 28: Chodov - Edges added (highlighted in green) to make all nodes at least in range of BPL

The resulting subgraph of chosen edges for Chodov district data sample is highlighted in Figure 29.

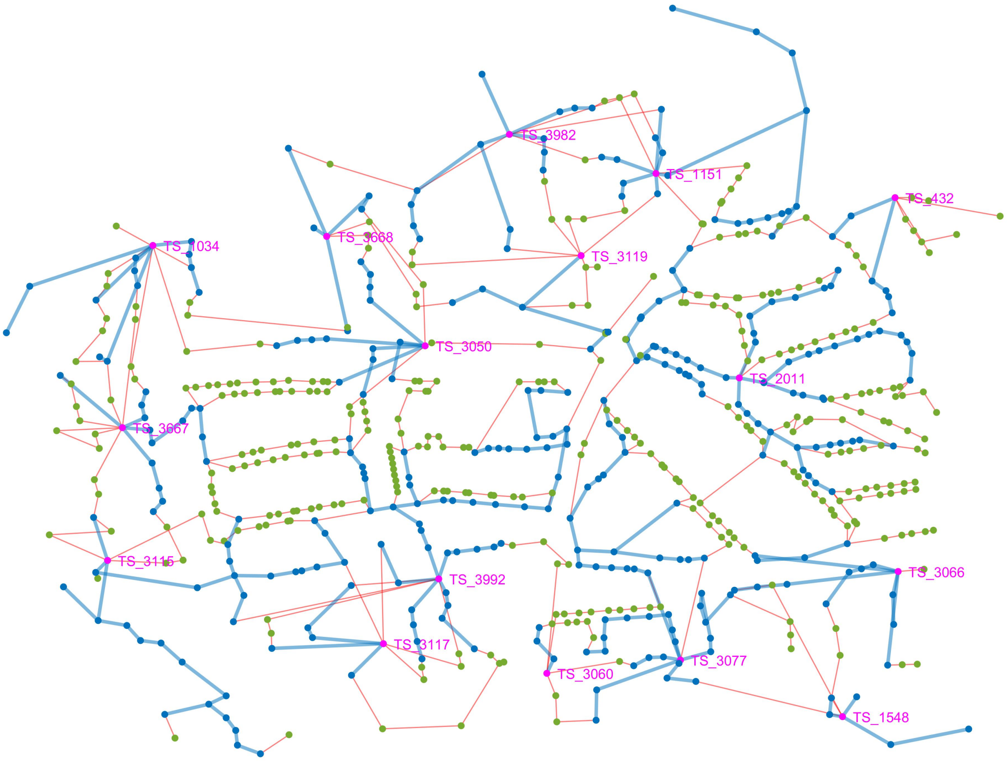

Figure 29: Chodov - BPL in combination with optical network resulting graph - edges not chosen (red), edges chosen for optical connection (blue), nodes directly connected to the optical network (blue, magenta), nodes with no direct connection to the optical network but in range of BPL (green)

The pseudocode for the BPL and optical network combination method is given on the next page.

Pseudocode

```
1. Make graph G based on dataset provided, use lengths of the cables as weights of edges.
2. Set BPL range R (R = 200 m used in simulations).
3. Identify node types - secondary substations, distribution points, fuse cabinets.
4. Mark all secondary substation nodes as directly connected to the optical network – set node attribute ‘Connected’ = 1.
5. Mark all other nodes than secondary substation nodes as not connected – set node attribute ‘Connected’ = 0.
6. Mark all edges in the graph G as not chosen – set edge attribute ‘Chosen’ = 0.
7. For each distribution point:
    • Find the shortest path p to the nearest (in terms of cable length) connected node.
    • Mark nodes on the shortest path p as directly connected to the opt. network - set attribute ‘Connected’ for these nodes to 1.
    • Mark edges of the shortest path p as chosen – set attribute ‘Chosen’ to 1.
8. While there are nodes which are not connected – set of attributes ‘Connected’ for nodes in G contains zero(s):
    • Get set of nodes N in graph G which are nor in range, nor directly connected – nodes with attribute ‘Connected’ = 0.
    • Identify nodes N_in_R in set of nodes N which are in range of PLC (in range = shortest path in terms of length to the nearest directly connected node is shorter or equal to the range parameter R).
    • Mark N_in_R as “in range” nodes - set attribute ‘Connected’ to 2.
    • Remove N_in_R from N.
    • If N not empty:
        ○ Get the shortest path to the nearest directly connected point for each node in N = set of paths P_not_connected.
        ○ Pick the longest path p = $[n_1, n_2, n_3..., n_{L-1}, n_L]$ in terms of cable length from P_not_connected (p is a path of L nodes where $n_1$ is directly connected node and $n_L$ is nor connected, nor in range).
        ○ “Push” connection towards $n_L$:
            - Mark $n_2$ as directly connected – set ‘Connected’ = 1.
            - Mark edge of path p between nodes $n_1$ and $n_2$ as chosen – set ‘Chosen’ = 1.
9. G_new = remove not chosen edges (’Chosen’ $\neq$ 1) from G.
10. G_new = result.
```

7 Results and economic evaluation

This chapter summarises the results of different optical network design methods from previous chapter and provides their individual economic evaluations.

7.1 Graph coverage obtained by different methods

The graph coverage results of all three examined samples are shown below. These results were directly reflected in the total investment costs of building the fibre-optic communication network in the economic evaluation.

Chodov district coverage results

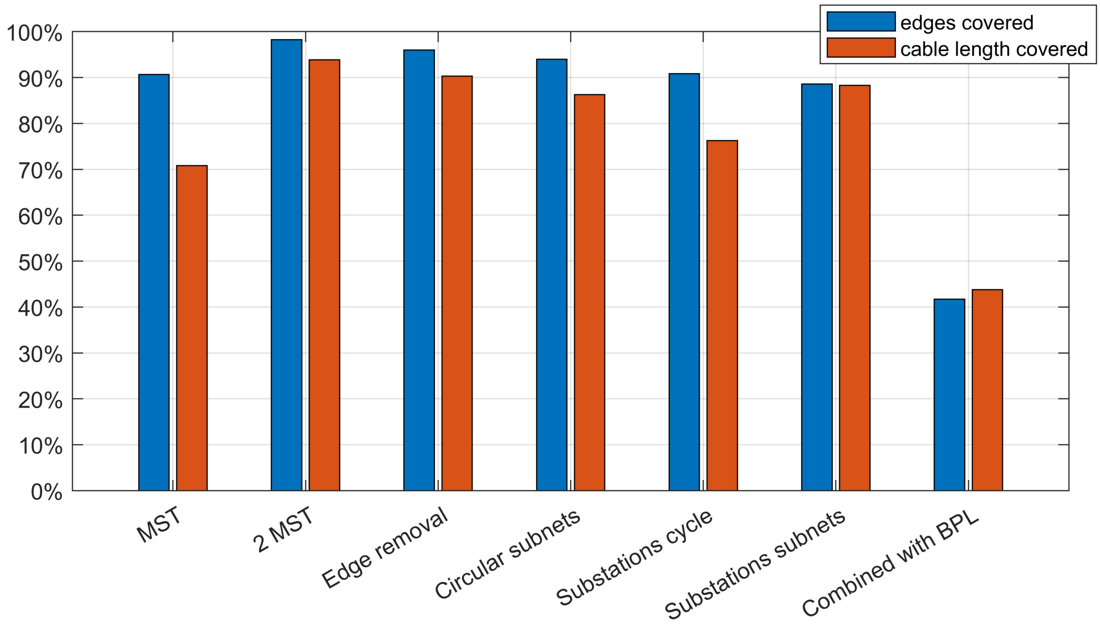

Figure 30: Chodov - Percentage of edges and cable length covered

Figure 30 shows the results of Chodov district sample. As expected, the lowest weighted result for algorithms interconnecting all the sample nodes[2] was obtained in case of finding minimum spanning tree (MST). Approximately 70% of the cable length needed to be covered with an optical network to interconnect all the nodes.

Spanning trees with added links method (2 MST) included more than 98% of the total number of edges in the graph thus covering approximately 93% of the total length of the given sample's connections and creating significant redundancy, which was reflected in the overall cost when using this approach.

Edge removal method shows slightly better results with approximately 96% of edges chosen and 90% of cable length covered, but still creating considerable redundancy.

The method of searching for a cycle involving all secondary substations - nodes connecting MV and LV level networks - and circular subnetworks (Circular subnets) offers slightly less

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[2] MST, 2 MST, Edge removal method, Circular subnets, Secondary substations cycle

redundancy than the two previously mentioned methods, and hence a lower percentage of cable length covered (around 86% of link length covered).

Another method, where a cycle involving all secondary substations was initially selected and then the rest of the nodes were connected to that cycle without intentionally creating redundancy (Substations cycle), produced results almost identical to the minimum spanning tree search.

The method of creating separate secondary substation subnetworks (Substations subnets) not interconnecting all the sample nodes covers approximately 88% of edges and 88% of cable length. Despite the fact that this method is choosing fewer edges to install optical cable in than the MST or the all secondary substations cycle method (both 90%), the cable length coverage of the secondary substation subnetworks method is higher than the cable length coverages of the two methods (70% for MST and 76% for the substations cycle method). Nevertheless, the economic evaluation shows that this method results in slightly lower total investment cost than the costs of the two methods. Even though the secondary substations subnetworks method adds to the cost of cabling, it reduces the cost of terminations compared to the MST and the all secondary substations cycle method since it does not interconnect all the sample nodes. This applies also to the results of the other two samples mentioned below.

Obviously, the last method, that uses optical connection in combination with BPL, results in the overall lowest coverage in case of both edges picked (41%) and cable lengths covered (43%). Of course, this result is conditioned by the fact that this method assumes a considerable use of BPL at the LV level.

Nové Město district coverage results

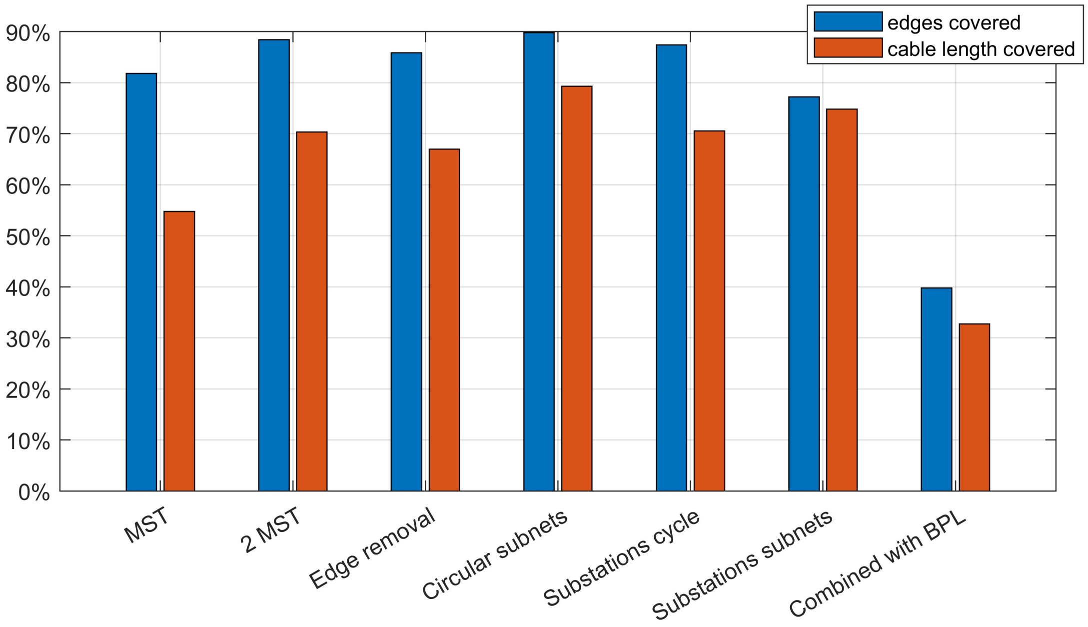

Figure 31: Nové Město - Percentage of edges and cable length covered

Figure 31 shows the results of Nové Město district sample. Also here, the lowest weighted result for algorithms interconnecting all the sample nodes was obtained in case of finding minimum spanning tree - 82% of edges and 55% of cable length covered.

The two minimum spanning trees with added links covered 88% of edges and 70% of cable length. Compared to the Chodov district sample, this method was suited better for this sample possibly due to the sample grid structure, but still creating considerable redundancy compared to other methods applied to the Nové Město district sample.

Again, the edge removal method shows slightly better results with approximately 85% of edges chosen and 67% of cable length covered, but still creating considerable redundancy compared to MST.

Unlike for the Chodov district data sample, here the circular subnetworks method (90% of edges and 79% of cable length covered) and the secondary substations cycle method (87% of edges and 71% of cable length covered) result in higher coverage than the three previously mentioned methods. The reason is the structure of the sample graph - it contains 2 subgraphs connected in one point. Thus, when looking for the longest cycle in the beginning of the algorithms, the cycle covers only one half of the sample. That results in creating more redundancy in next steps of the algorithms than in applying these algorithms to the other two samples.

The method of creating separate secondary substation subnetworks covers 77% of edges and 75% of cable length and behaves similarly as described above for the Chodov district sample.

The method of combining optical network with BPL gives the overall lowest coverage results for this sample but this time the percentage of cable length covered (33%) is lower than the percentage of edges chosen (40%).

Vinohrady district coverage results

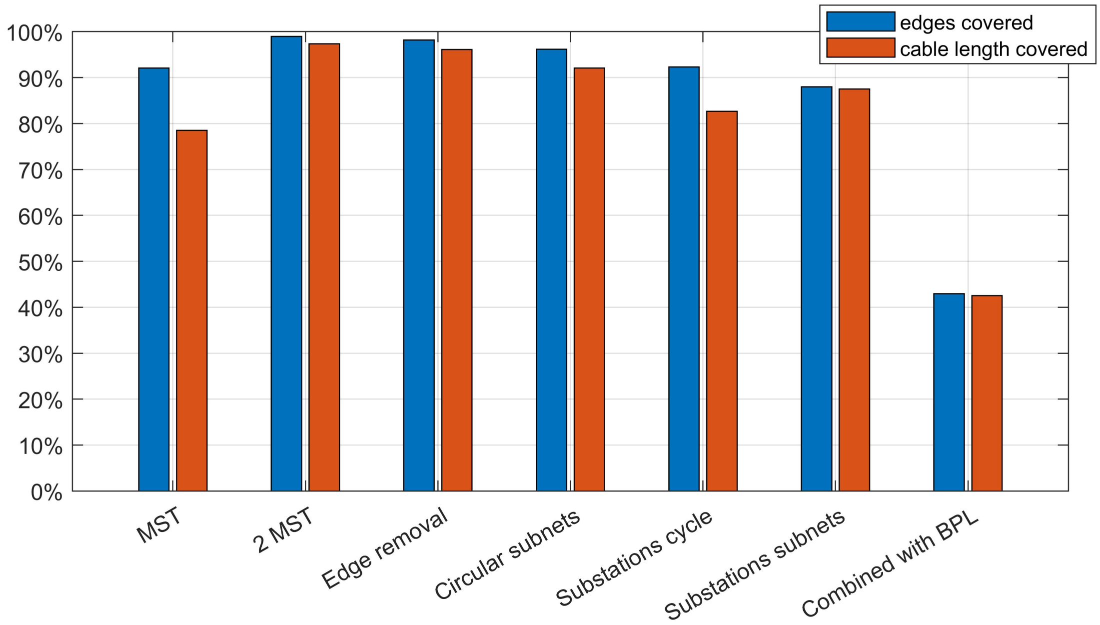

Figure 32: Vinohrady - Percentage of edges and cable length covered

The Vinohrady district sample results are depicted in Figure 32. The results are almost identical with the Chodov district sample results.

Spanning trees with added links method creates the highest redundancy (almost 99% of edges chosen and 97% of cable length covered).

Edge removal method shows again slightly better results with approximately 98% of edges chosen and 96% of cable length covered.

The method of searching for a cycle involving all secondary substations and circular subnetworks offers slightly less redundancy than the two previously mentioned methods (96% of edges chosen and 92% of cable length covered).

The results for the minimum spanning tree and secondary substations cycle method are almost identical (92% of edges chosen and 79% of cable length covered in case of MST and 92% of edges chosen and 82% of cable length covered for secondary substations cycle method) as it was also in case of the Chodov district sample.

The method of creating separate secondary substation subnetworks covers 88% of edges and almost 88% of cable length and behaves similarly as described above for the Chodov district sample.

The method considering use of BPL gives the overall lowest coverage results for this sample as well but this time with the percentage of cable length covered (42%) being almost the same as the percentage of edges chosen (43%).

7.2 Economic evaluation

The objective of the economic evaluation is to evaluate each solution option from Chapter 6 for the LV level of each power grid sample. The economic evaluation of the individual options is based on a comparison of the cumulative total investment costs for the implementation of the optical communication network, without taking into account the prices of nodes (passive splitters, active switches and other elements). For the comparison of the different options, only the prices of the passive structure up to the termination at the patch panel are considered. It is not addressed how much and what kind of telecommunications equipment must be installed. In the evaluation only the termination at the node (for both sides of the cable) is taken into account, i.e. the actual termination of the optical cable (patch panels, connectors, welds, measurements) - the price depends on the number of optical fibers (the size of distribution panels, the number of welds and the number of measurements grow linearly with the number of fibers installed).

The key inputs to the economic evaluation model are the lengths and numbers of cables (edges in the graphs) and the prices of the optical network elements and their installation. The prices considered are given in Table 1.

Table 1: LV level - prices of optical communication network elements and installation

Task/element	**Cost in €/m**
HDPE tube	2,00
Optical cable (48 fibres)	0,80
Attaching HDPE tube and blowing fibre optic cable	2,00
Blowing fibre optic cable into the already prepared HDPE tube	0,80
Task/element	**Cost in €/pc**
Welding	4,00
Connector	1,60
Patch panel	80,00
Measurements	9,20

The evaluation is based on the considered cost at the LV level according to [11], where the considered cost is 4,80 €/m of the optical network implemented in the form of an attachment (approx. 2 €/m for the HDPE tube, 2 €/m for the installation and 0,80 €/m for the optical cable with 48 fibres). The evaluation also takes into account whether the edge already contains an empty HDPE tube/HDPE tube with installed optical cable or not. In the case that an empty HDPE tube is already in place, the considered cost is 1,60 €/m (approx. 0,80 €/m for a 48-fibre fibre optic cable and 0,80 €/m for the blowing). The sections of the samples that already contain optical cables are not included in the considered investment.

Based on these inputs, the investment costs are calculated for every sample and summarised in Figures 33, 34 and 35.

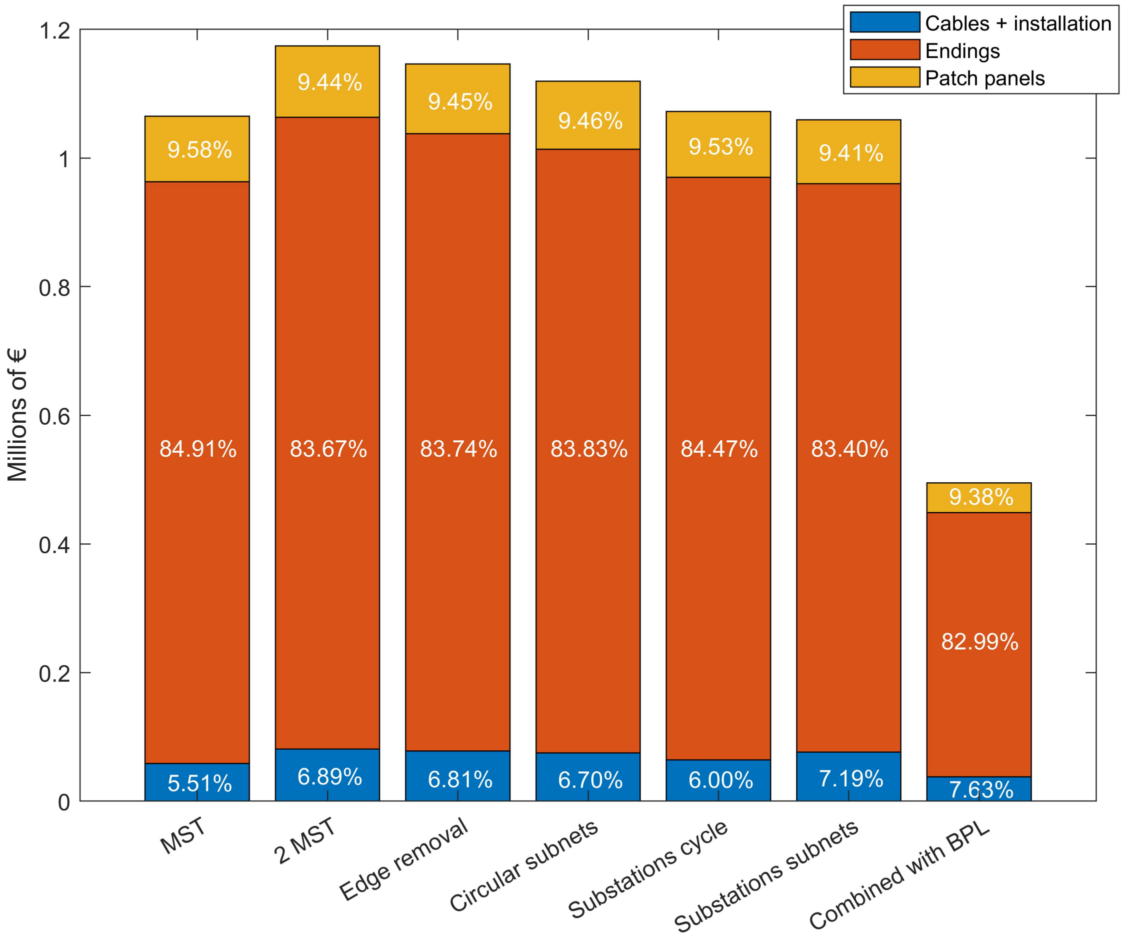

Figure 33: Chodov - Total investment costs for different methods of optical network design

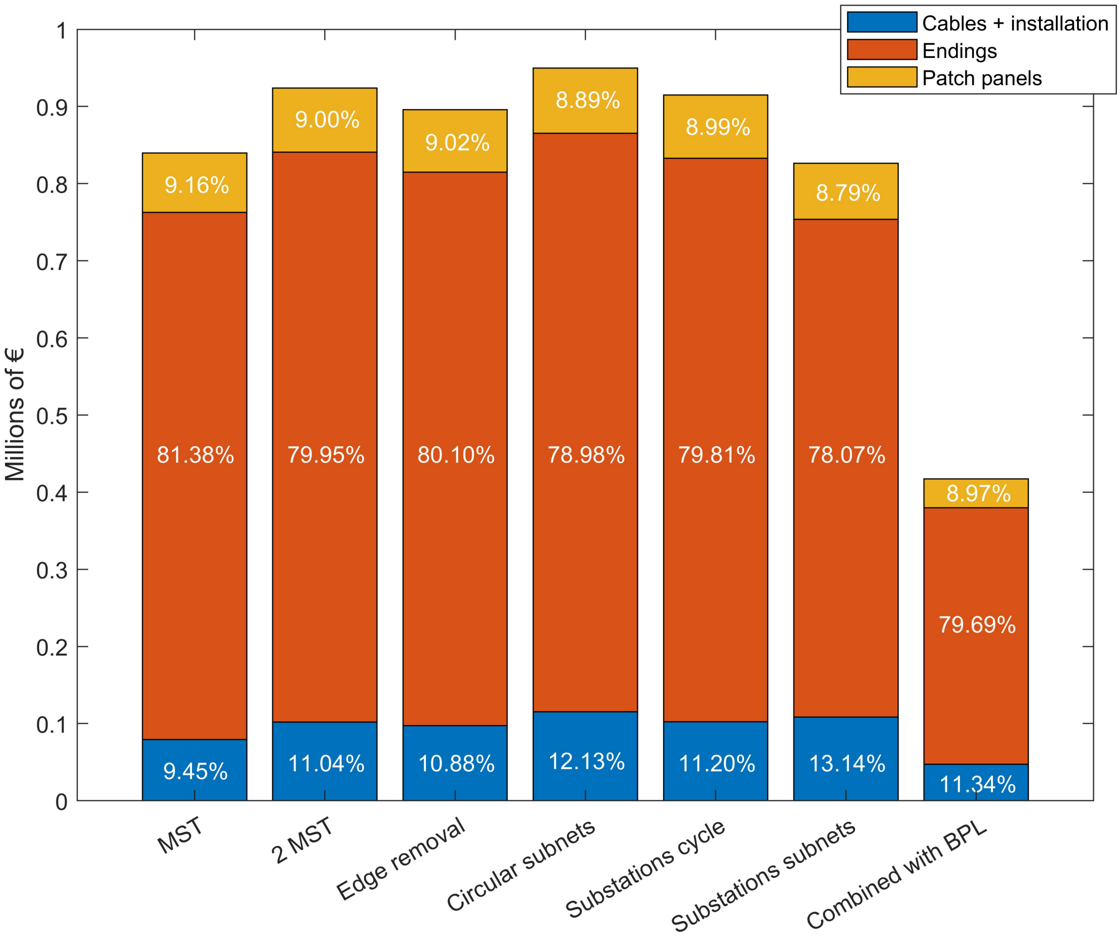

Figure 34: Nové Město - Total investment costs for different methods of optical network design

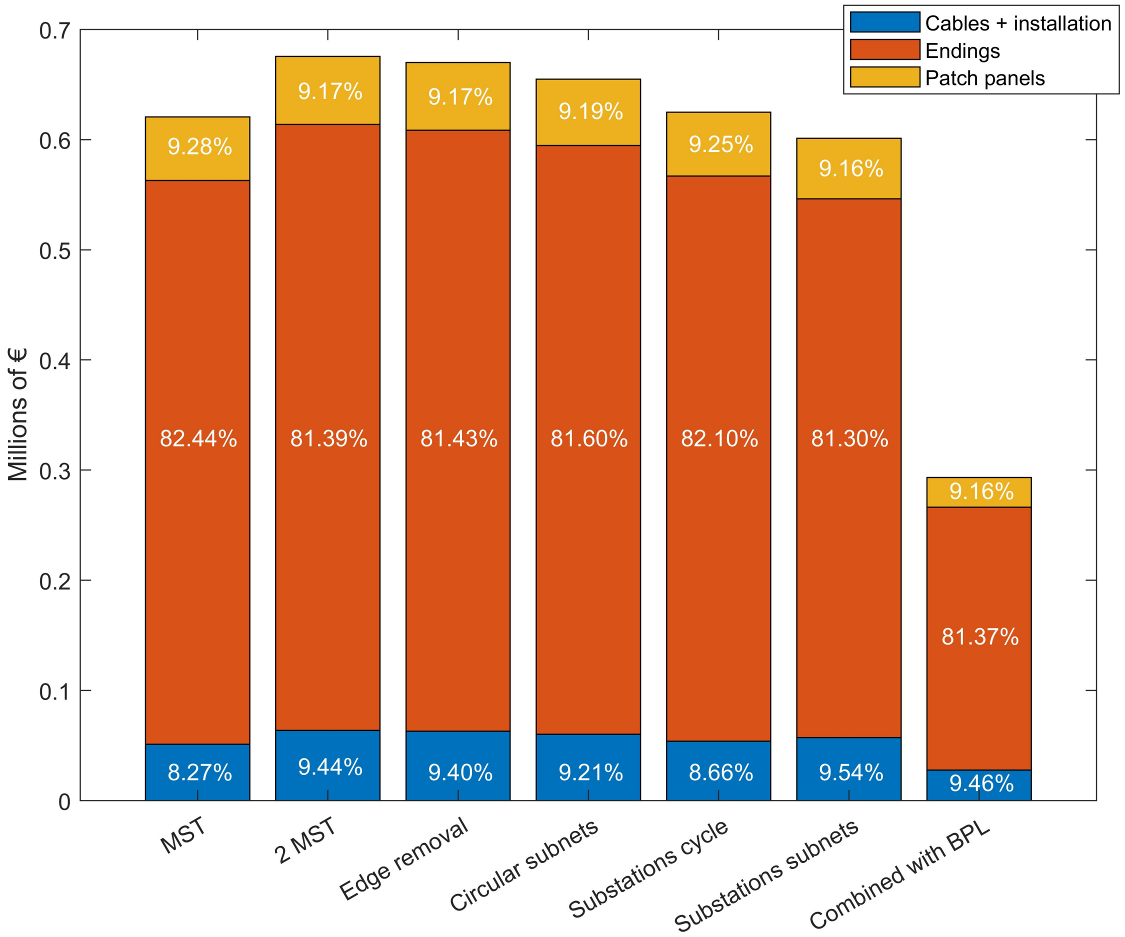

Figure 35: Vinohrady - Total investment costs for different methods of optical network design

Figures 33, 34 and 35 show the cumulative total investment costs of different methods for building the accompanying optical communication network for Smart Grid. The total amount of the investment costs is influenced by the extent of the telecommunication network to be built. The extent of the network to be built is determined by the number of power elements covered by the telecommunication network and the length of fibre optic lines built. Since the total investment costs depend on the extent of the network to be built, graph coverage in Figures 30, 31 and 32 is directly reflected in Figures 33, 34 and 35. The higher the cable redundancy - the higher the costs. This applies with one exception which is the secondary substations subnetworks method showing higher cable redundancy than some methods but resulting in lower total cost than those methods due to lower total endings cost:

- MST is showing the best result among the methods which are interconnecting all the nodes. This applies to all samples. However, the price to achieve these lowest costs is practically zero redundancy (a spanning tree does not provide the possibility to physically back up transmission paths).
- On the contrary, in case of Chodov and Vinohrady data samples, the 2 MST supplemented by multiple links give the highest redundancy and hence the highest costs among all the methods.
- Edge removal method achieves a slightly better result than 2 MST while preserving redundancy for backing up the network and hence the additional links in case of the previously mentioned method seem to be unnecessary.
- The circular subnetworks method offers a compromise between lowest cost MST and completely backed up circular topology achieved by edge removal procedure - this applies to Chodov and Vinohrady data samples. The investment cost is still significantly higher than for MST option but the majority of nodes in this solution is a part of a smaller circular subnetwork connected to the cycle including all secondary substations (backhaul nodes) which results in most of the nodes being part of the backed up subnetwork. However, this method gives the highest redundancy and total cost in case of the Nové Město data sample due to the structure of this particular data sample.
- The secondary substations cycle method gives almost identical results as the MST option but with at least some backup circular network for secondary substations - this, again, applies only to Chodov and Vinohrady data samples. The question is whether this option provides enough reliability by putting all the substations into one circular subnetwork. For similar reasons as in the previous point, in the case of the Nové Město data sample, this method results in overall higher total cost than when applying it to the other two data samples.
- Secondary substations subnetworks method, one of the methods that does not interconnect all the data sample nodes, results in the lowest total cost among the methods that are assuming direct connection to optical network for all sample nodes. Despite the higher cable redundancy than MST or the secondary substations cycle method, the total cost for this method is lower than the total costs of the two methods. Even though the total cable cost for this method is higher, the total cost of endings is lower. Since the costs of terminations create the most significant amount of the total costs, in the end, the total cost for this method is lower than the resulting total cost of MST or the secondary substations cycle method.
- The method of combining optical communication infrastructure with BPL gives the overall lowest total investment costs for building an optical network in case of all data samples.

For all samples, in all seven cases, the majority of the total investment costs (approximately 80%) is the investment in fibre optic terminations, i.e. the cost of connectors, welds and control measurements. The costs of cabling, including installation, is only around 6 - 10% of the total costs.

The large cost of cable terminations is due to the nature of the network at LV levels where the path lengths are relatively short. The fibre demand for energy applications is relatively low (typically 48 (96) fibres in a cable of which only a quarter is terminated and the rest is kept as a reserve). To reduce high termination costs, it is possible to terminate only a subset of fibres in optical cables since for example AMM needs only few fibres to operate. Another way to reduce fibre usage is to use passive optical network and/or CWDM technology.

8 Conclusion

The aim of the thesis was to analyze the possibilities for building communication infrastructure in the context of Smart Grid with a focus on optical networks and connection of technological area with economic analysis. The work is based on the National Action Plan for Smart Grid approved by the Government of the Czech Republic and on studies developed for the needs of the energy distributor PREdi.

The first part of the thesis deals with the study of the concept of Smart Grid. It defines the Smart Grid and gives a brief description of its main characteristics, stating that nowadays the power cable does not only serve the function of electricity supply, but also creates an element of communication infrastructure. Thus, the paper presents the communication challenges and the main impulses for the development of communication networks for the power industry, emphasizing the importance and need for communication at all levels of the power grid. It also provides an overview of transmission media and technology types applicable in Smart Grid, presents advantages and disadvantages of each technology along with recommendations for technology selection for different levels of the power grid.

The thesis focuses in detail on optical communication within the Smart Grid. In the theoretical part, it discusses the need of optical communication for Smart Grids at different levels of the power grid, presents an overview of the used optical fibers and cables, technologies and possibilities of their installation within the power grid, taking into account the cost of the installation methods.

The thesis then focuses on the design of the optical network for the needs of the electricity distributor - PREdi. The aim of the company is the smartening of the distribution network and the creation of smart infrastructure carried out in accordance with the National Action Plan for Smart Grids with focus mainly on the smartening of MV/LV secondary substations and the development of fibre optic infrastructure. The thesis presents a current status and a brief description of PREdi network structure at MV and LV level.

The work then focuses on a methodology for selecting a suitable subset of LV network links to install optical infrastructure. First, multiple methods to find the optimal topology of the supporting overlapping optical network for Smart Grid have been described. Most of the methods are based on graph theory and on the assumptions of a certain typical form of the already built power grid LV layer (circular subnetworks, high redundancy). Some of the methods assume an existing interconnection of secondary substations at the MV level or use of other technology in combination with fibre optics communication.

Subgraphs of the power grid graph were found and edges (cables) were selected to interconnect either all nodes or at least a necessary number of nodes of the network sample at the lowest possible cost. In particular, the different approaches varied in the degree of redundancy of the selected solution for the optical network, ranging from essentially zero redundancy for optical links to practically inefficient approaches creating unnecessary redundancy for backed up optical communication. The results presented in the thesis are for the approaches that aimed to minimize the lengths of the selected cables, since the cost of cabling and its installation increases linearly with the length of the sections. For a more advanced optimization, it would be more appropriate to start not from a metric that takes into account the length of the sections but the cost of the construction and to base it on the annual allocation of investment funds.

The different path-finding procedures in the graph were applied to the three district samples of the distribution network at LV level operated by the electricity distributor PREdi. Each method resulted in a subnetwork of selected LV network links. For each of these subnetworks, the approximate investment costs for its construction were calculated. The different solutions were then compared in terms of cable redundancy (potential reliability) and total cumulative costs. The economic analysis of the construction of the optical network at LV level also confirmed that in all cases a large part of the cost has to be taken into account for the termination of the optical fibres at the communicating points.

Except for the method of finding the minimum possible topology for the physical interconnection of network nodes (minimum spanning tree search), all the other methods interconnecting all sample nodes at the LV level were based on the attempt to at least partially back up the communication network and thus to find circular topologies of different range, while still trying to minimize the total length of the links selected for the installation of the optical communication infrastructure while connecting all the nodes.

There is a large number of connection points at the lower level of the network, so network planning needs to be efficient. Not all LV power cables will have fibre optics. The redundancy of the LV power network is significant. Higher level hierarchies require greater robustness and reliability but for LV level a minimum spanning tree infrastructure may be sufficient. In terms of cost, the minimum spanning tree approach is undoubtedly the most attractive among the examined possibilities that optically interconnect all the sample nodes. However, it has to be considered whether this approach is sufficient in terms of back up. If greater reliability of the communication network is required, a trade-off between cost, the extent of back-up and feasibility is necessary.

If interconnection of secondary substations on the MV level is assumed and interconnection of all sample nodes is not a necessity, the secondary substations subnetworks method results in even lower total investment costs than above mentioned MST due to savings in termination costs.

To decrease the total costs of optical network building even more, the combination of optical connection and BPL was explored resulting in significant cost reduction of more than 40% in some cases. Hence, the last examined method seems to be the most interesting from the overall economic evaluation point of view. It should be remembered that this method involves the use of optical communication infrastructure in combination with BPL technology. Although BPL uses already existing power line infrastructure and the communication network can be established quickly and cost-effectively, BPL has its limitations too - the range is highly dependent on the network topology, the level of interference and the condition of the cables. However, BPL is a suitable technology to use at the LV level at least until the installation of optical cables within the gradual reconstruction of power infrastructure thus reducing investment costs in the beginning.

The way the communication infrastructure is created significantly influences the development of smart solutions newly integrated into the distribution network, such as the development of post-smart stations, AMMs, electromobility charging points, etc. In this work, we considered the scenario of each node being considered as an end point - fibre optics was introduced to all endpoints and also another possible scenario in which optics was used in combination with another technology to serve other communicating points in range of BPL via power cables. The results show that different methods performed differently for different data samples due to their specific topology.

References

[1] ITU-T. *Recommendation G.652: Characteristics of a single-mode optical fibre and cable.* International Telecommunications Union, Geneva, 11/2016.

[2] ITU-T. *Recommendation G.657: Characteristics of a bending-loss insensitive single-mode optical fibre and cable.* International Telecommunications Union, Geneva, 11/2016.

[3] *PREdistribuce, a. s./Annual Report 2020.* PREdistribuce, a. s., Prague, Czech Republic, 2021. Translated from Czech.

[4] Fredrik Ege Abrahamsen, Yun Ai, and Michael Cheffena. *The Enhancement of Communication Technologies and Networks for Smart Grid Applications.* March 2014. Available at `https://arxiv.org/abs/1403.0530`. Accessed: 12/10/2021.

[5] Fredrik Ege Abrahamsen, Yun Ai, and Michael Cheffena. *Communication Technologies for Smart Grid: A Comprehensive Survey.* June 2021. Available at `https://arxiv.org/abs/2103.11657`. Accessed: 12/10/2021.

[6] G3-PLC Alliance. *G3-PLC Overview & Benefits.* Available at `https://g3-plc.com/g3-plc/`. Accessed: 09/02/2022.

[7] PRIME Alliance. *PRIME Alliance Technology leaflet.* Available at `https://www.prime-alliance.org/wp-content/uploads/2020/04/df-1-prime-1-collaterals-1-technology-insert-v12-digital.pdf`, 2020. Accessed: 09/02/2022.

[8] Batz/Stockmar. Staying big or getting smaller. *Energy Atlas 2018: Figures and Facts about Renewables in Europe*, May 2018. Available at `https://energytransition.org/2018/04/europe-must-choose-a-green-future/`. Accessed: 04/10/2021.

[9] Marcelo Blatt. Optical Communications for Improving the Performance and Reliability of the Smart Grid. *Electric Energy MAGAZINE*, 13(6):51–54, November/December 2009.

[10] Jan Bruinenberg, Larry Colton, Emmanuel Darmois, John Dorn, John Doyle, Omar Elloumi, Heiko Englert, Raymond Forbes, Jürgen Heiles, Peter Hermans, and Mathias Uslar. *CEN -CENELEC - ETSI: Smart Grid Coordination Group - Smart Grid Reference Architecture Report 2.0.* January 2012.

[11] DSO and TSO associations in cooperation with external consultants. *Design of a unified DSO telecommunications network: Measures of the NAP SG P13.* Ministry of Industry and Trade of the Czech Republic, Prague, Czech Republic, November 2018. Translated from Czech.

[12] Xi Fang, Satyajayant Misra, Guoliang Xue, and Dejun Yang. Smart Grid — The New and Improved Power Grid: A Survey. *IEEE Communications Surveys Tutorials*, 14(4):944–980, 2012.

[13] Hamid Gharavi and Reza Ghafurian. Smart Grid: The Electric Energy System of the Future [Scanning the Issue]. *Proceedings of the IEEE*, 99(6):917–921, 2011.

[14] V.C. Gungor and F.C. Lambert. A survey on communication networks for electric system automation. *Computer Networks*, 50(7):877–897, 2006.

[15] Petr Holubec. *Press release: Prague's energy network is modernizing - the number of its "smart" elements is increasing [online].* Pražská energetika, a. s., Prague, Czech Republic, October 2020.
Available at `https://www.pre.cz/cs/profil-spolecnosti/media/tiskove-zpravy/prazska-energeticka-sit-se-modernizuje-pocty-jejich-chytrych-prvku-se-zvysuji/`. Accessed: 16.09.2021. Translated from Czech.

[16] Mahtab Hosseininia and Faraz Dadgostari. Hamiltonian paths and cycles. *Graph Theory for Operations Research and Management: Applications in Industrial Engineering*, pages 96–105, 01 2012.

[17] Pavel Lafata and Jiří Vodrážka. *Optical access networks FTTx and NGA.* Czech Technical University in Prague, 2019. Translated from Czech.

[18] Jiří Matoušek and Jaroslav Nešetřil. *Chapters from discrete mathematics.* Charles University in Prague, Karolinum, 2009. Translated from Czech.

[19] Department of Electric Power and Heating. *National Action Plan for Smart Grids 2019 - 2030: Update NAP SG.* Ministry of Industry and Trade of the Czech Republic, Prague, Czech Republic, September 2019. Translated from Czech.

[20] Mathieu Tahon, Jan Van Ooteghem, Koen Casier, Lukas Deschuttere, Sofie Verbrugge, Didier Colle, Mario Pickavet, and Piet Demeester. Cost allocation model for a synergetic cooperation in the rollout of telecom and utility networks. In *10th Conference of Telecommunication, Media and Internet Techno-Economics (CTTE)*, pages 1–7, 2011.

[21] Jiří Vodrážka. *Analysis of issues related to the process of building optical networks at the MV level - Methodological support.* Czech Technical University in Prague, December 2019. Translated from Czech.

[22] Rehman Zafar, Anzar Mahmood, Sohail Razzaq, Wamiq Ali, Usman Naeem, and Khurram Shehzad. Prosumer based Energy Management and Sharing in Smart Grid. *Renewable and Sustainable Energy Reviews*, 82, July 2017.

Appendix

Types of edges covered by different algorithms

Tables 1, 2 and 3 summarise the results obtained by the different algorithms described in Chapter 6. They list the number of edges that were selected for the optical communication network for each sample (along with the percentage of edges covered in initial graphs[3]), indicating how many of the selected edges already contain optical cable or at least empty HDPE tube. They also give the resulting weight (length of links in kilometres) of the designs (also with the percentage of cable length covered in initial graphs for every sample).

Legend:
Edges - overall number and percentage of chosen edges,
HDPE - number of chosen edges with empty HDPE tube,
OPTO - number of chosen edges with already installed optical cable,
Weight - chosen subgraph weight = length in km and percentage of overall length covered

Table 1: Chodov - Different scenario coverage results

Method	Edges	HDPE	OPTO	Weight [km]
Initial graph	729 (100%)	583	24	36,32 (100%)
MST	661 (90,67%)	536	23	25,72 (70,81%)
2 MST	716 (98,22%)	577	23	34,09 (93,86%)
Edge removal method	700 (96,02%)	564	23	32,80 (90,31%)
Circular subnetworks	685 (93,96%)	548	23	31,33 (86,28%)
Secondary substations cycle	662 (90,81%)	535	23	27,70 (76,28%)
Secondary substations subnets	646 (88,61%)	520	23	32,07 (88,30%)
Combination with BPL	304 (41,70%)	240	14	15,89 (43,76%)

Table 2: Nové Město - Different scenario coverage results

Method	Edges	HDPE	OPTO	Weight [km]
Initial graph	588 (100%)	2	0	30,31 (100%)
MST	481 (81,80%)	2	0	16,60 (54,76%)
2 MST	520 (88,44%)	2	0	21,32 (70,34%)
Edge removal method	505 (85,88%)	0	0	20,29 (66,96%)
Circular subnetworks	528 (89,80%)	1	0	24,04 (79,32%)
Secondary substations cycle	514 (87,41%)	1	0	21,38 (70,54%)
Secondary substations subnets	454 (77,21%)	2	0	22,67 (74,81%)
Combination with BPL	234 (39,80%)	2	0	9,92 (32,72%)

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[3] sample graphs after modifications as described in 6.2

Table 3: Vinohrady - Different scenario coverage results

Method	**Edges**	**HDPE**	**OPTO**	**Weight [km]**
Initial graph	391 (100%)	6	0	13,77 (100%)
MST	360 (92,07%)	6	0	10,82 (78,52%)
2 MST	387 (98,98%)	6	0	13,41 (97,38%)
Edge removal method	384 (98,21%)	6	0	13,24 (96,10%)
Circular subnetworks	376 (96,16%)	6	0	12,69 (92,10%)
Secondary substations cycle	361 (92,33%)	6	0	11,39 (82,66%)
Secondary substations subnets	344 (87,98%)	5	0	12,05 (87,52%)
Combination with BPL	168 (42,97%)	3	0	5,86 (42,53%)

Other samples graph results of procedures from Chapter 6

Below are the intermediate results and the resulting graphs for the samples from the districts of Nové Město and Vinohrady (Figure 1) for each method described in Chapter 6.

Figure 1: Nové Město and Vinohrady - Multiple separate components distinguished by different colours

Nové Město

Minimum spanning tree

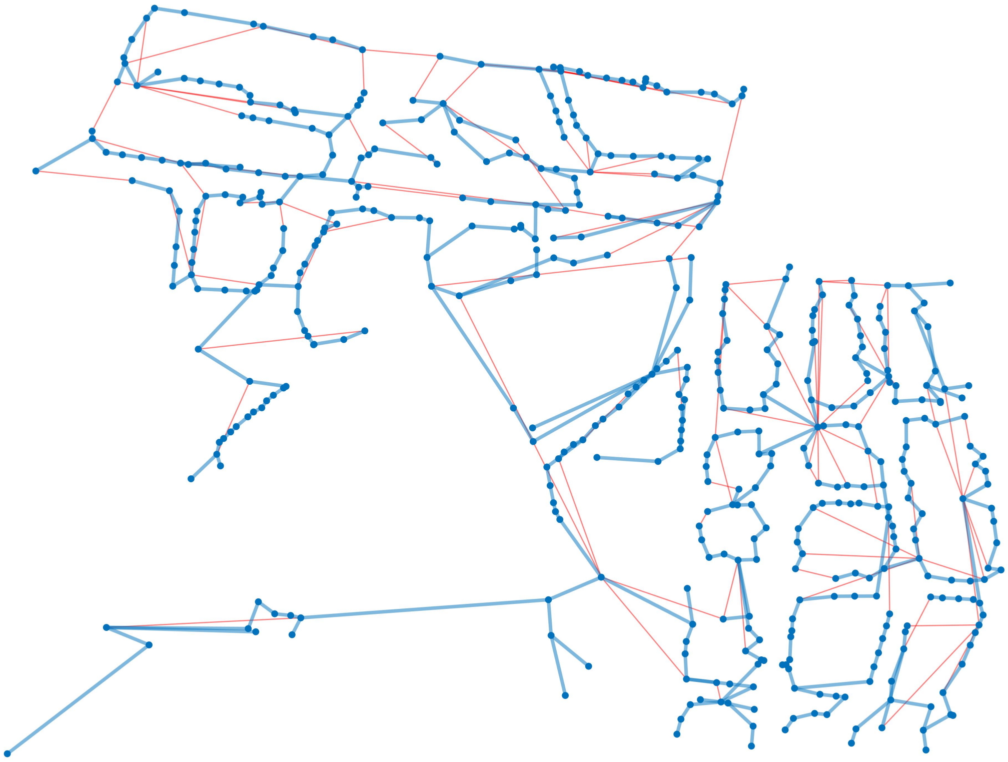

Figure 2: Nové Město - Minimum spanning tree (blue) and not chosen links (red)

Spanning trees with added links

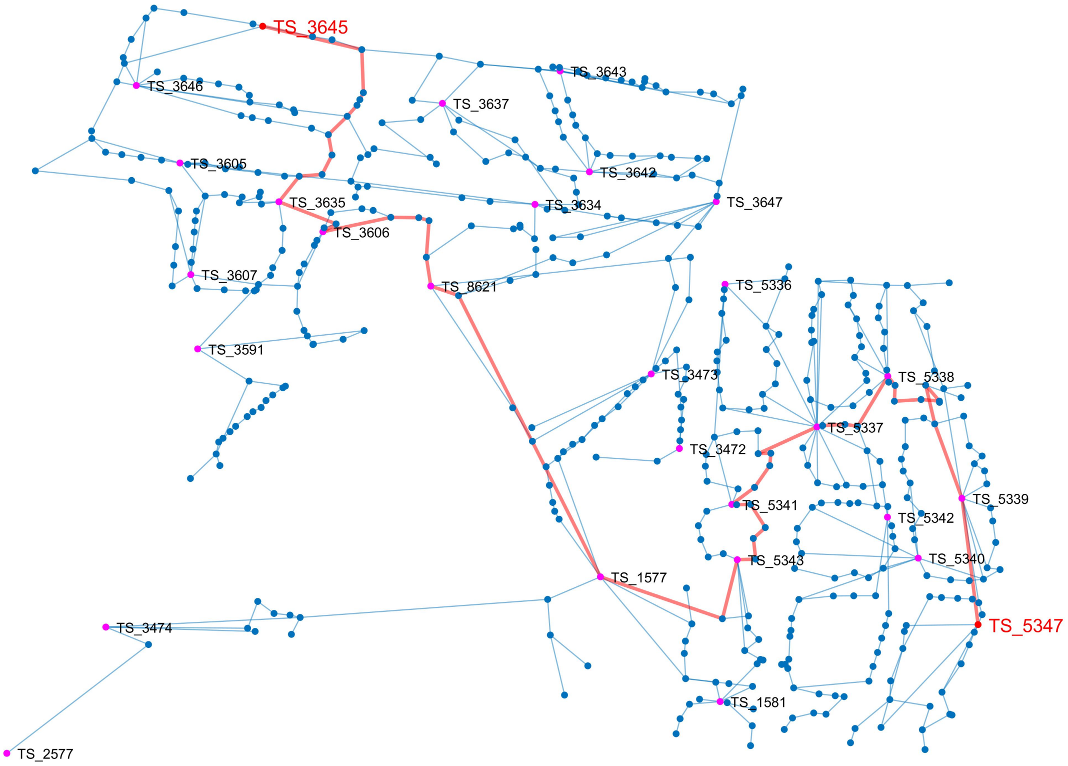

Figure 3: Nové Město - Chosen root nodes (red) and shortest path between them (also red)

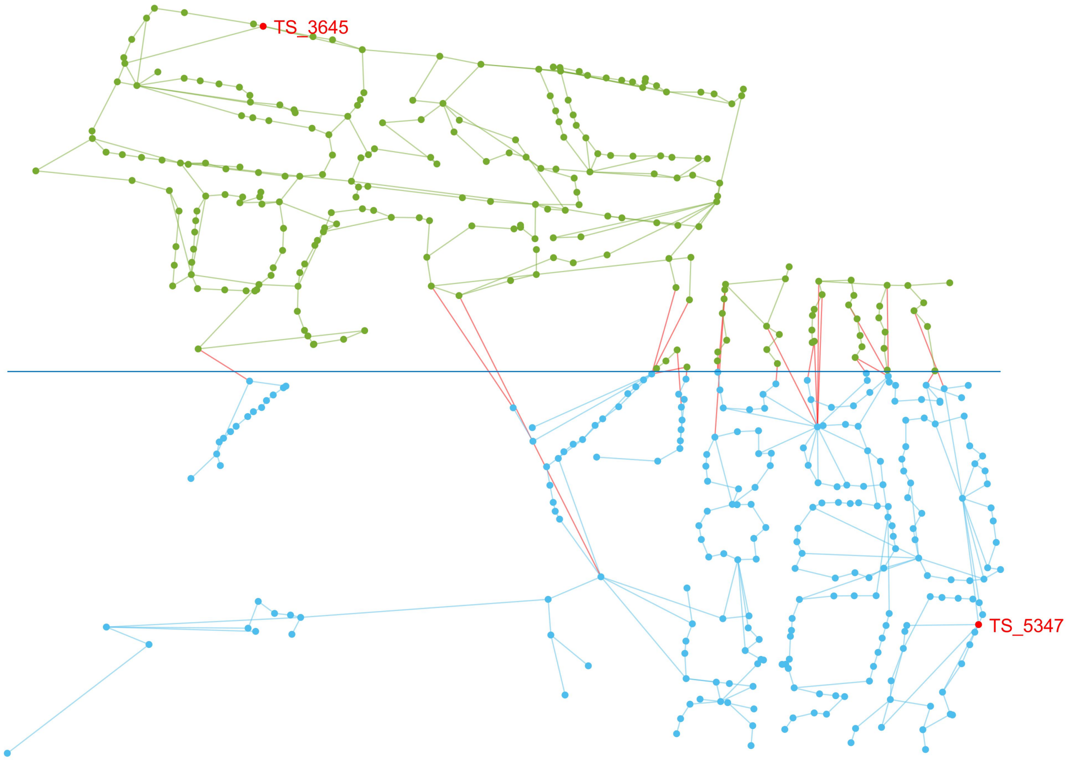

Figure 4: Nové Město - Two subsets of nodes (light blue and green) with links between them (red) divided by borderline (dark blue)

Figure 5: Nové Město - Two spanning trees (green and blue) and potential conjunctions (red)

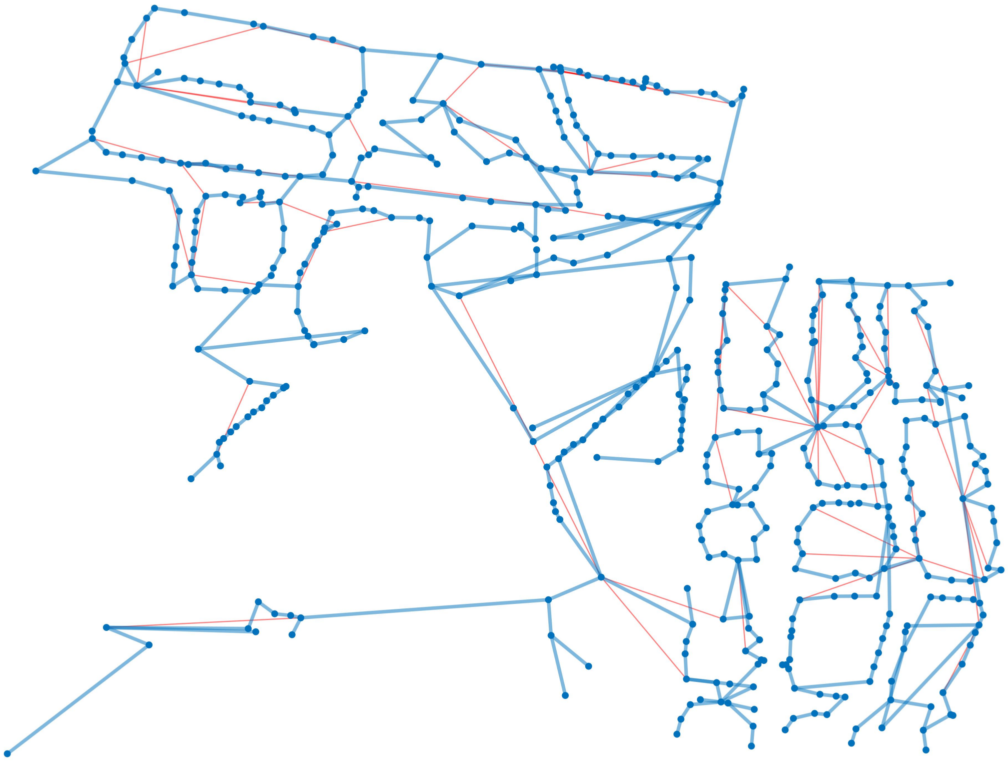

Figure 6: Nové Město - Spanning trees with added links (blue) with edges that were not chosen (red)

Edge removal method

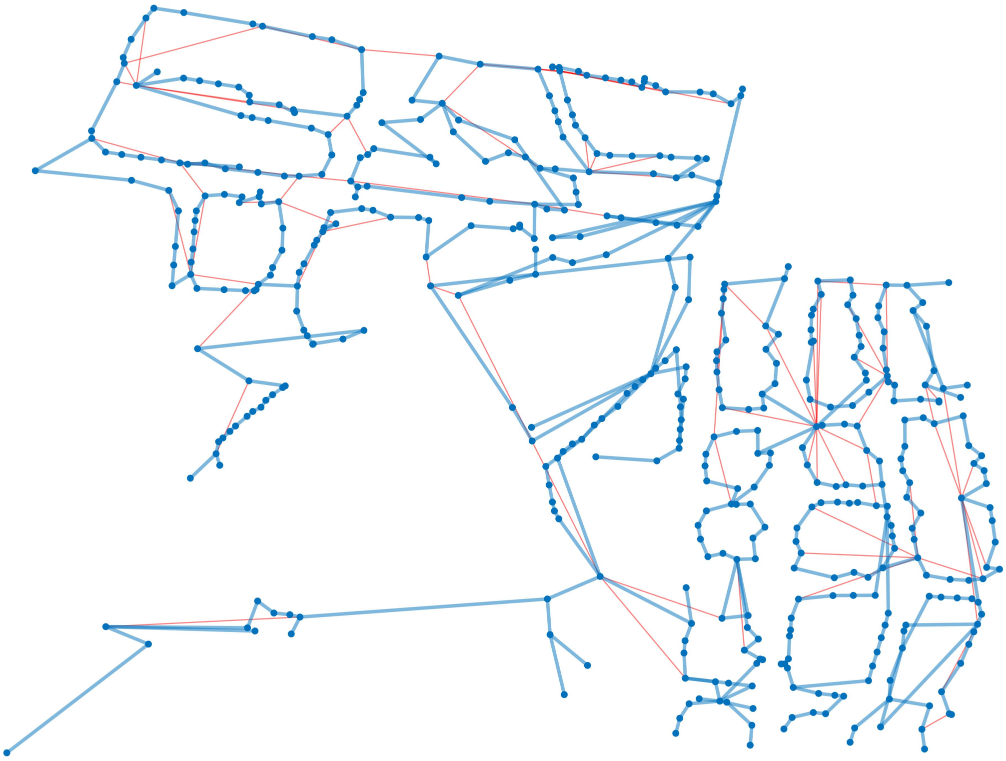

Figure 7: Nové Město - Edge removal method resulting graph (blue) with edges that were not chosen (red)

Circular subnetworks

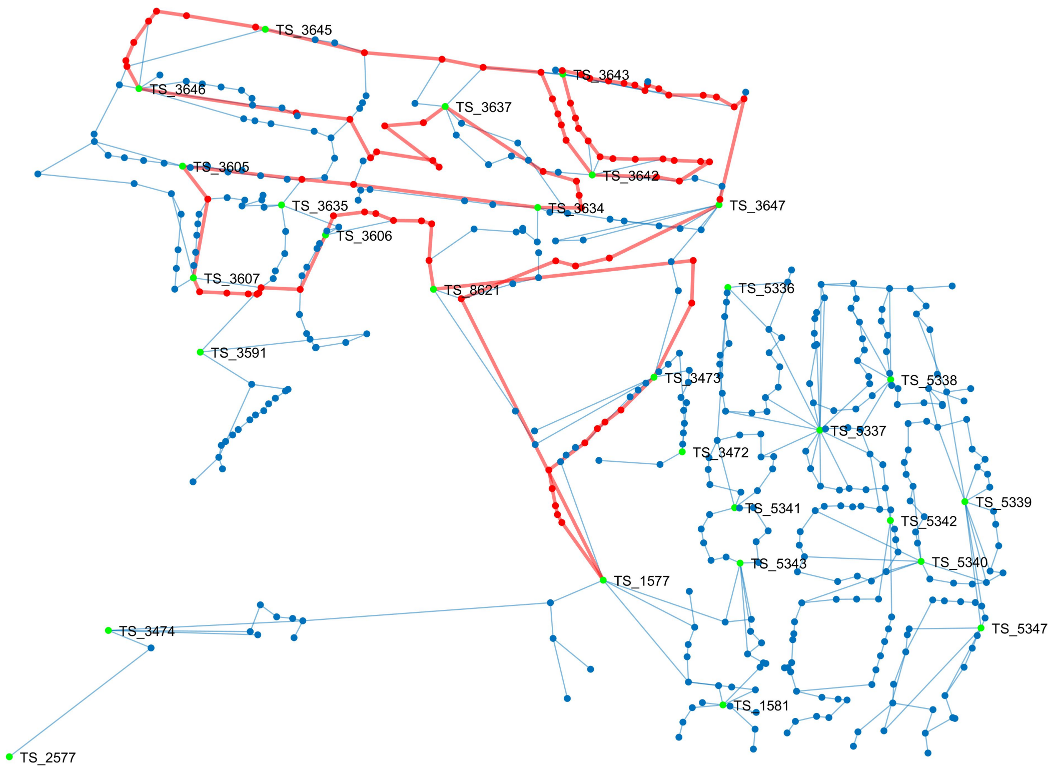

Figure 8: Nové Město - Cycle (red edges) of 100 nodes passing through almost half of secondary substations (green nodes)

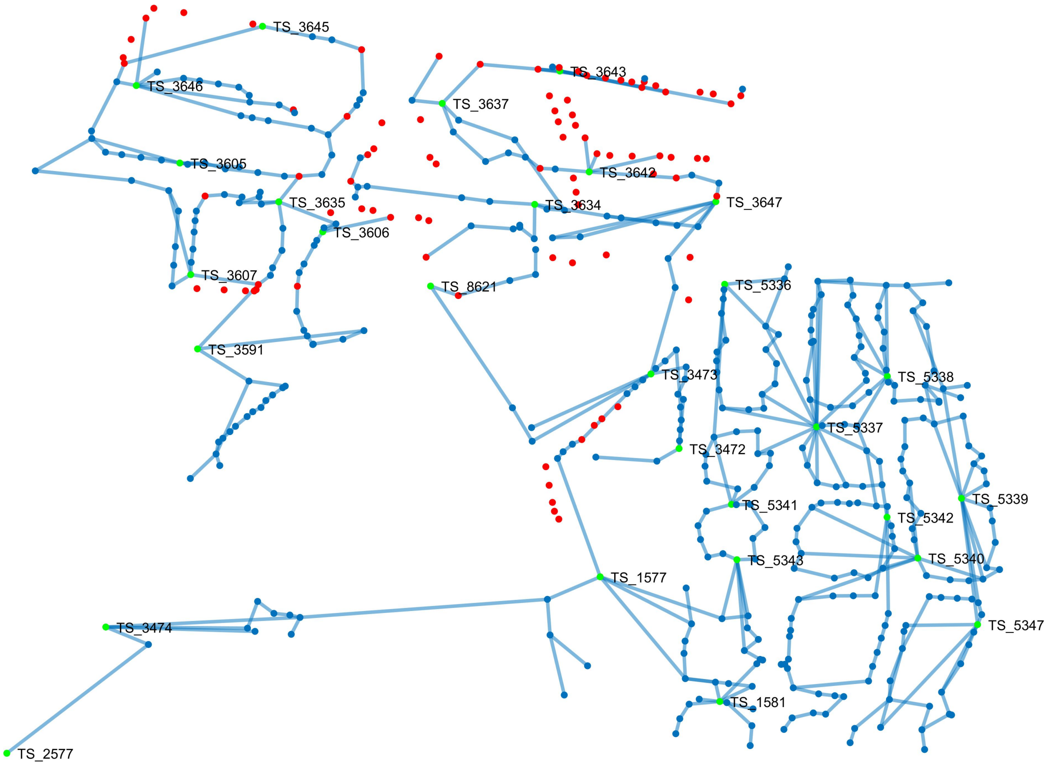

Figure 9: Nové Město - Edges left (blue) after removing the (red) edges of cycle highlighted in Figure 8

Figure 10: Nové Město - All cycles picked (red) and remaining nodes to connect (blue)

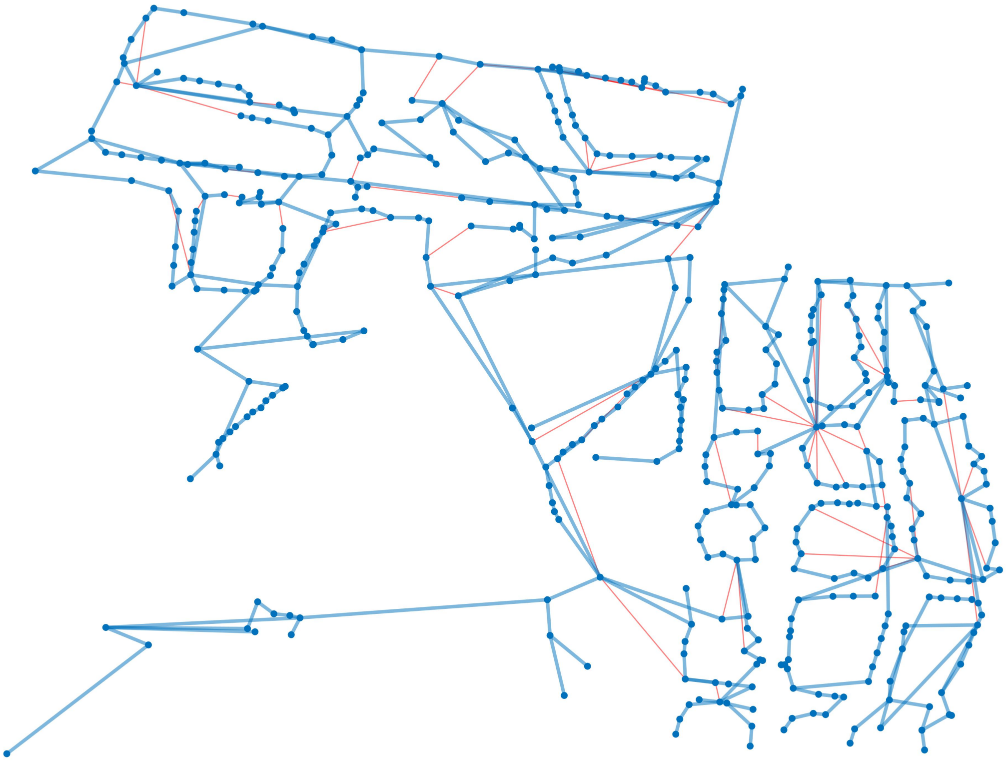

Figure 11: Nové Město - Circular subnetworks result - chosen (blue) and not chosen (red) edges

Secondary substations cycle

Figure 12: Nové Město - All secondary substations cycle result - chosen (blue) and not chosen (red) edges

Secondary substations subnetworks

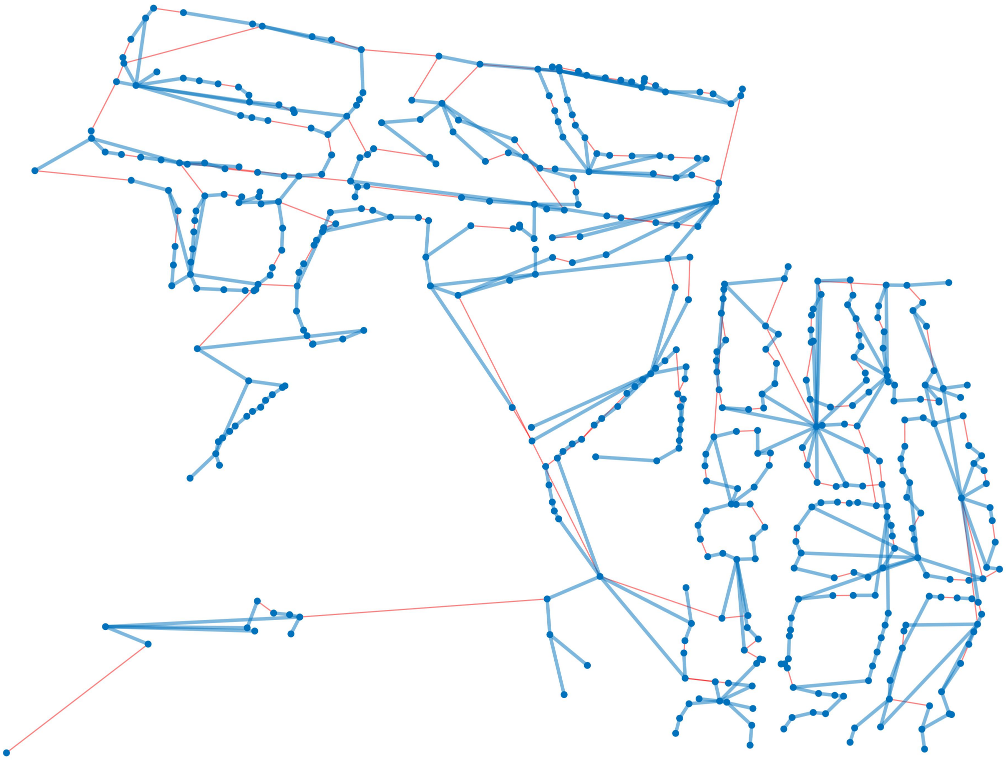

Figure 13: Nové Město - Secondary substations subnetworks result - chosen (blue) and not chosen (red) edges

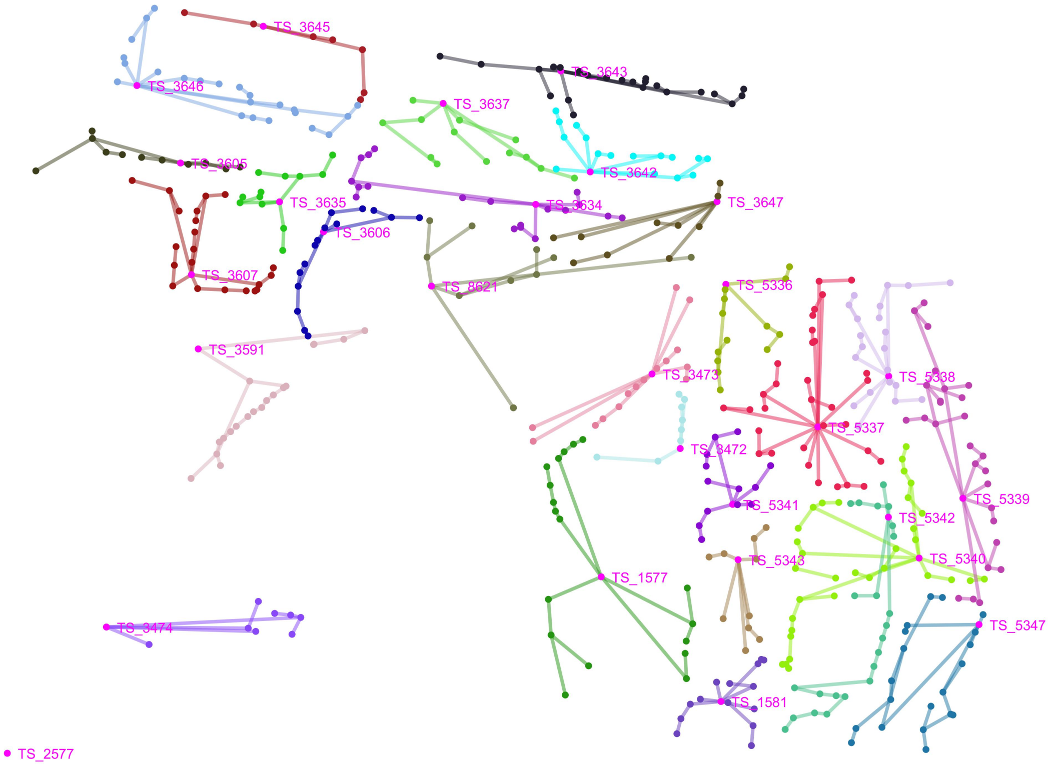

Figure 14: Nové Město - Secondary substations subnetworks highlighted in different colours

BPL and optical network combination

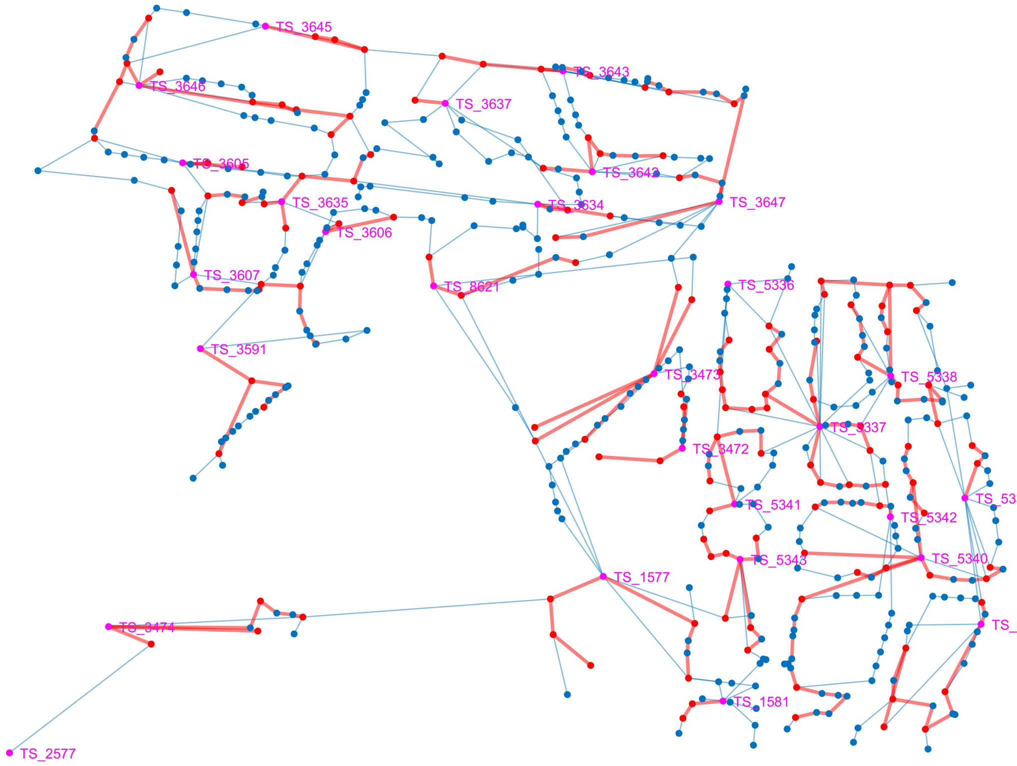

Figure 15: Nové Město - Distribution points (red nodes) directly connected with the optical connection (shortest paths highlighted in red) to the nearest secondary substation (magenta nodes)

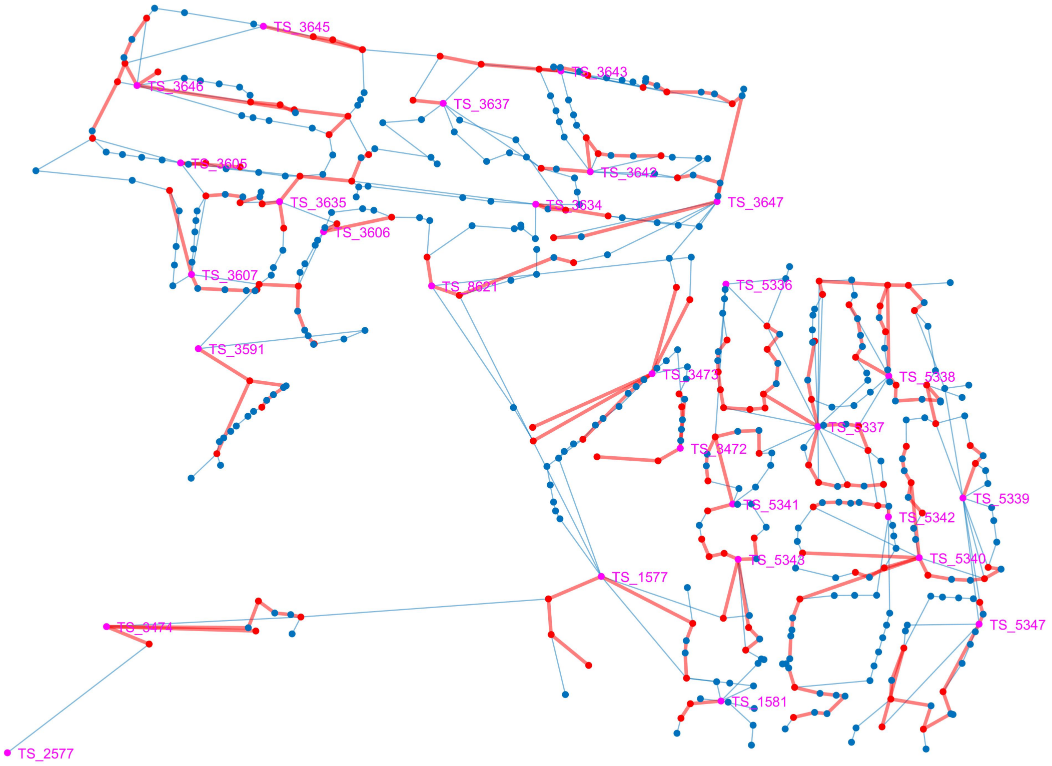

Figure 16: Nové Město - Edges added (highlighted in green) to make all nodes at least in range of BPL (no edges added in this step)

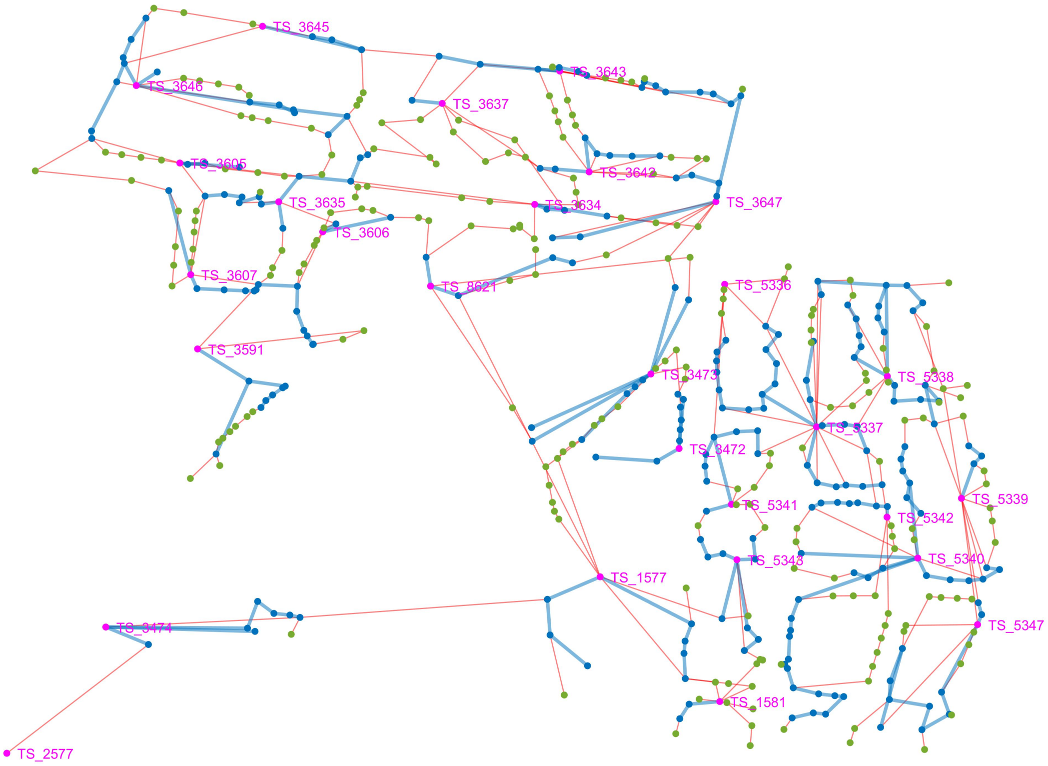

Figure 17: Nové Město - BPL in combination with optical network resulting graph - edges not chosen (red), edges chosen for optical connection (blue), nodes directly connected to the optical network (blue, magenta), nodes with no direct connection to the optical network but in range of BPL (green)

Vinohrady

Minimum spanning tree

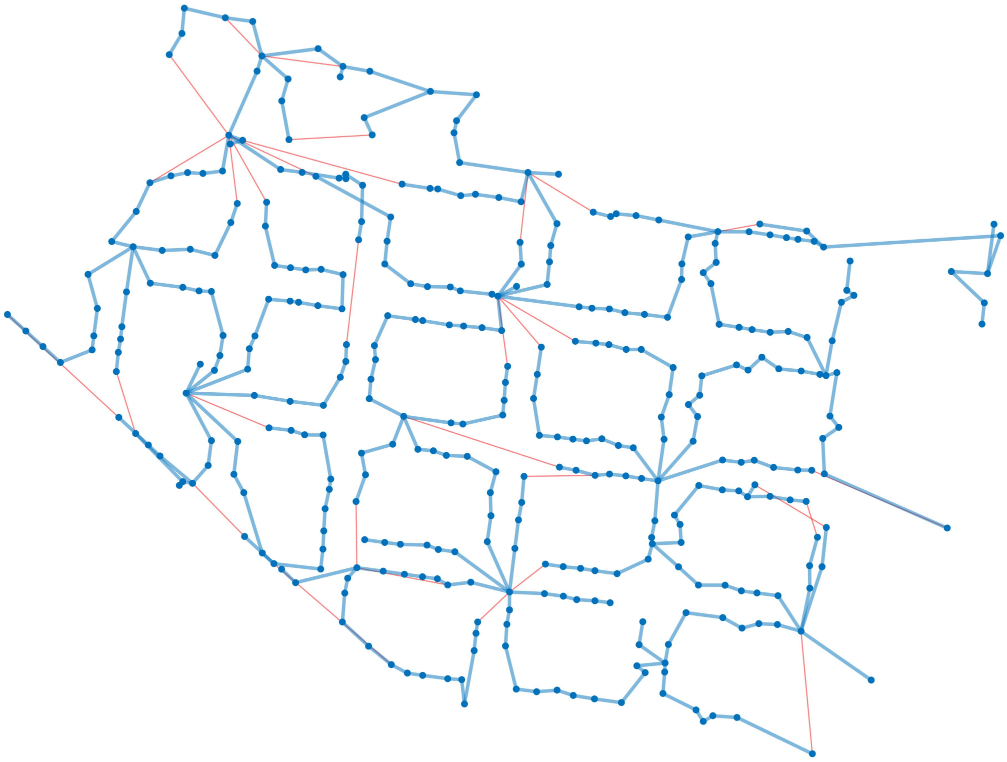

Figure 18: Vinohrady - Minimum spanning tree (blue) and not chosen links (red)

Spanning trees with added links

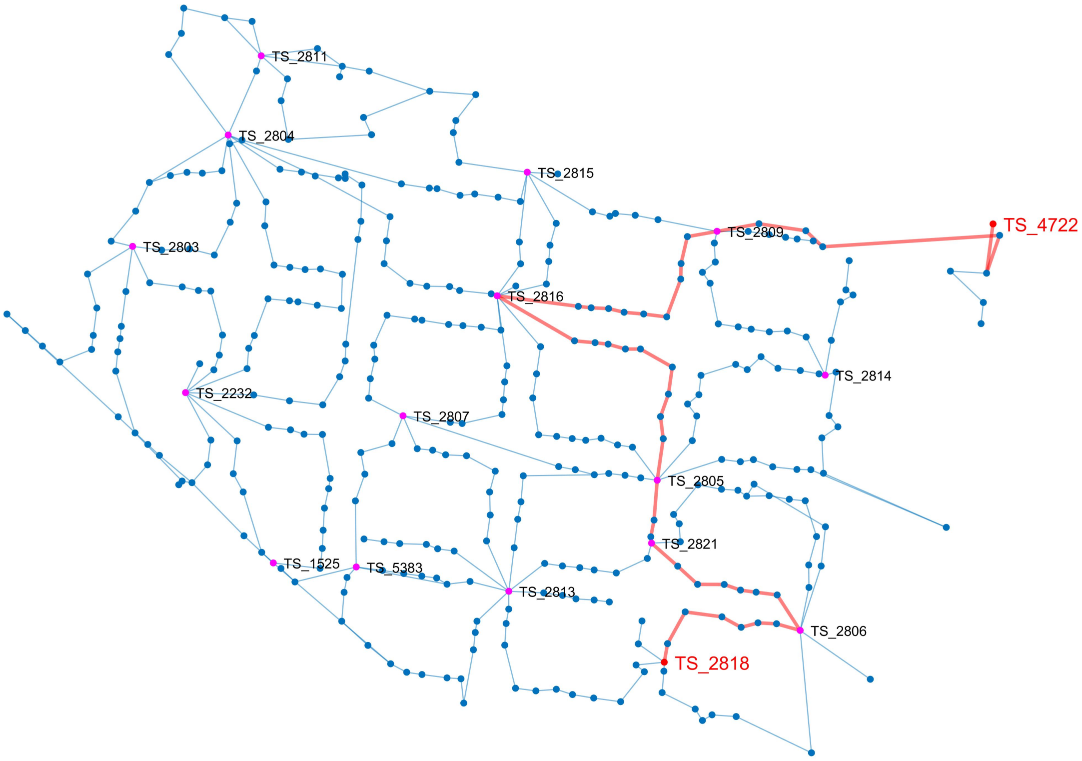

Figure 19: Vinohrady - Chosen root nodes (red) and shortest path between them (also red)

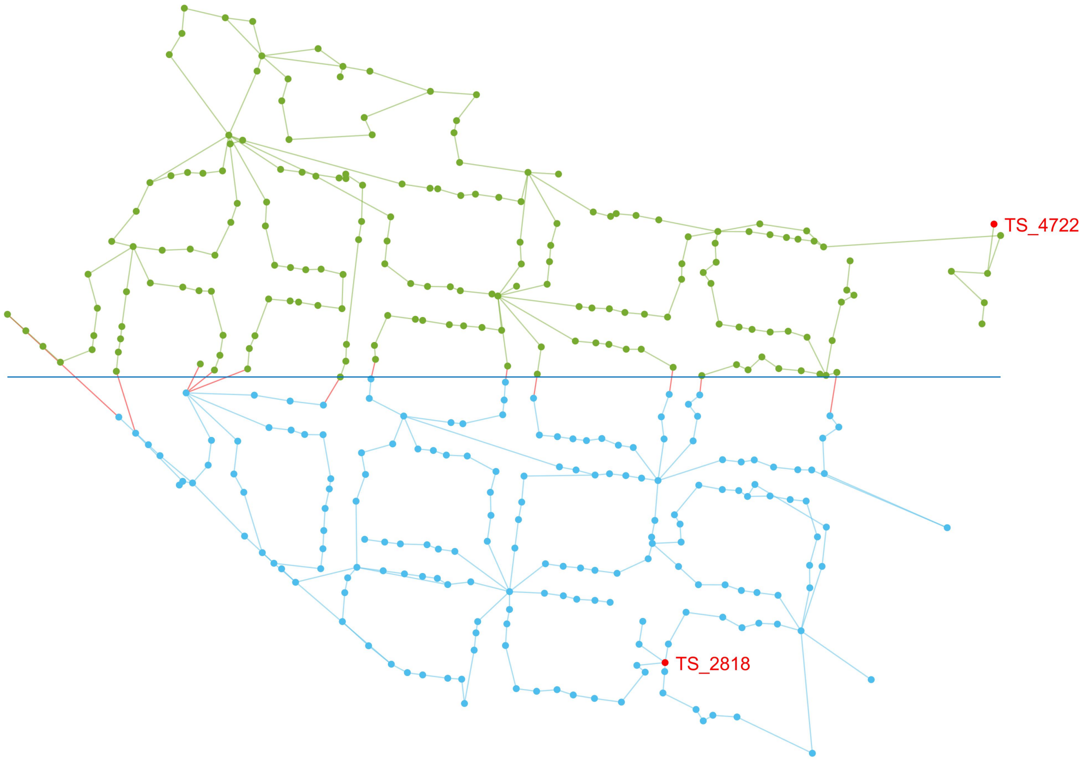

Figure 20: Vinohrady - Two subsets of nodes (light blue and green) with links between them (red) divided by borderline (dark blue)

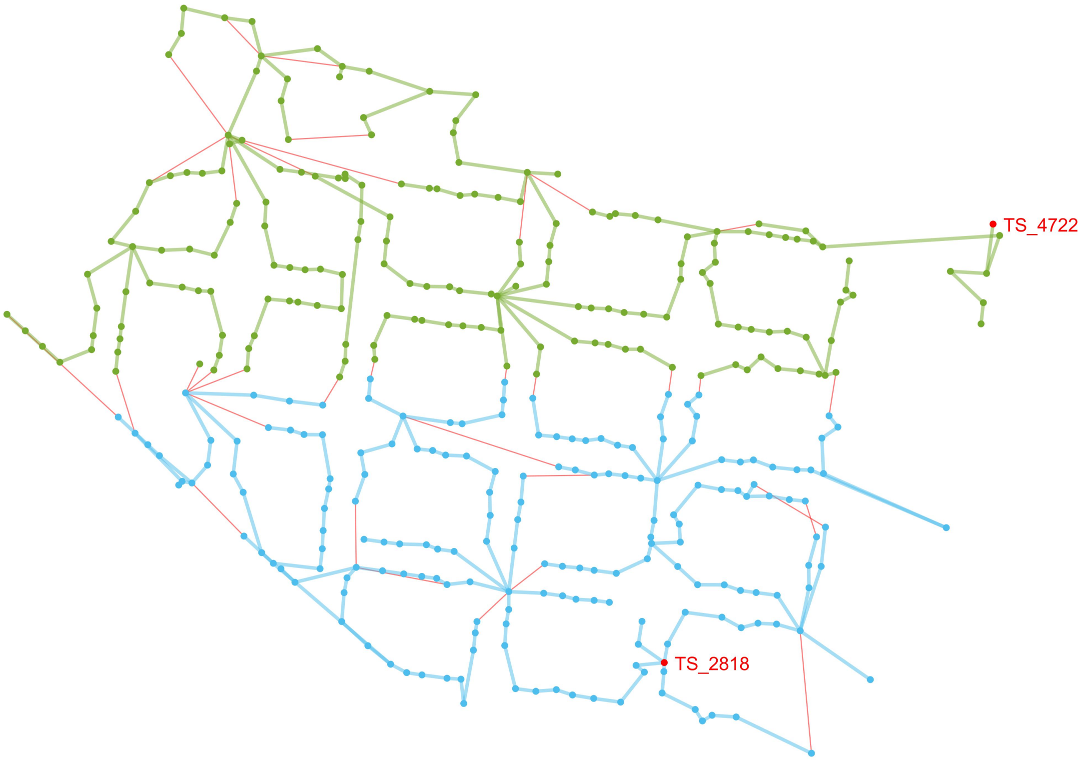

Figure 21: Vinohrady - Two spanning trees (green and blue) and potential conjunctions (red)

Figure 22: Vinohrady - Spanning trees with added links (blue) with edges that were not chosen (red)

Edge removal method

Figure 23: Vinohrady - Edge removal method resulting graph (blue) with edges that were not chosen (red)

Circular subnetworks

Figure 24: Vinohrady - Cycle (red edges) of 150 nodes passing through almost all secondary substations (green nodes)

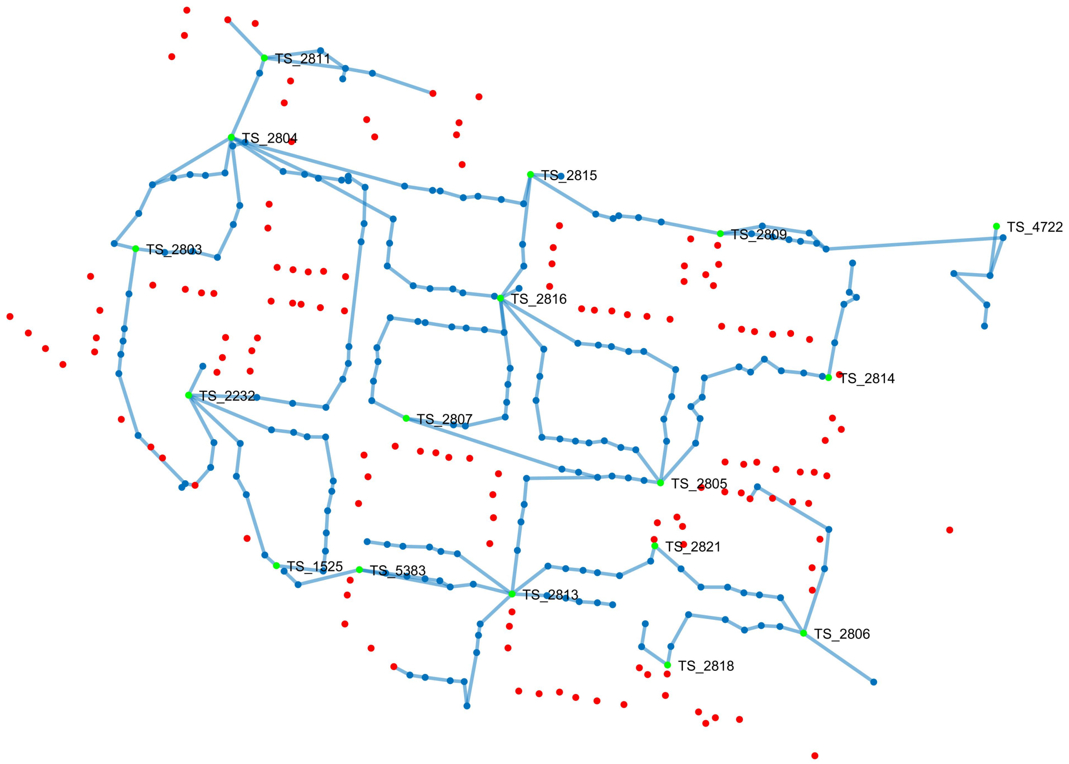

Figure 25: Vinohrady - Edges left (blue) after removing the (red) edges of cycle highlighted in Figure 24

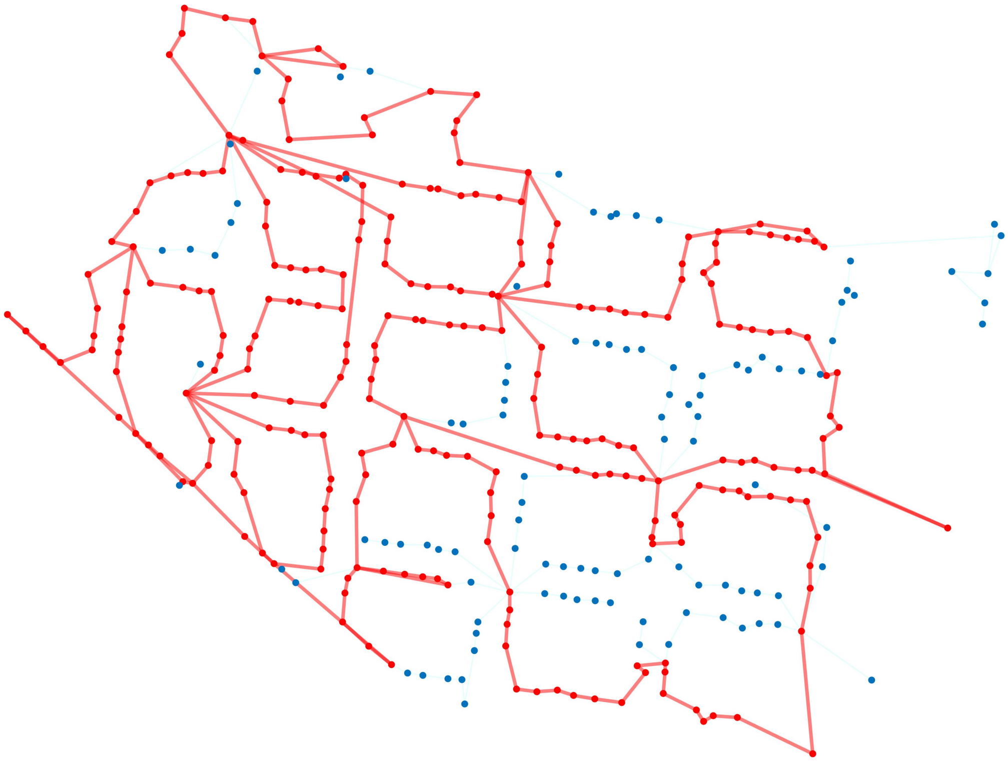

Figure 26: Vinohrady - All cycles picked (red) and remaining nodes to connect (blue)

Figure 27: Vinohrady - Circular subnetworks result - chosen (blue) and not chosen (red) edges

Secondary substations cycle

Figure 28: Vinohrady - All secondary substations cycle result - chosen (blue) and not chosen (red) edges

Secondary substations subnetworks

Figure 29: Vinohrady - Secondary substations subnetworks result - chosen (blue) and not chosen (red) edges

Figure 30: Vinohrady - Secondary substations subnetworks highlighted in different colours

BPL and optical network combination

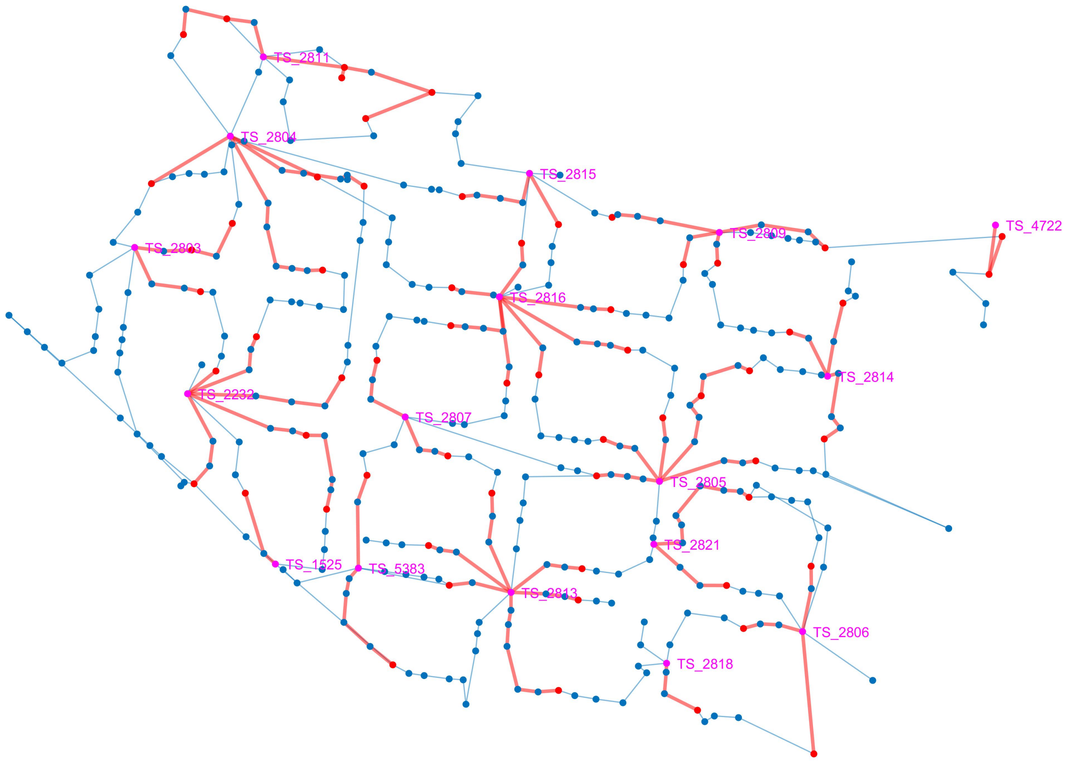

Figure 31: Vinohrady - Distribution points (red nodes) directly connected with the optical connection (shortest paths highlighted in red) to the nearest secondary substation (magenta nodes)

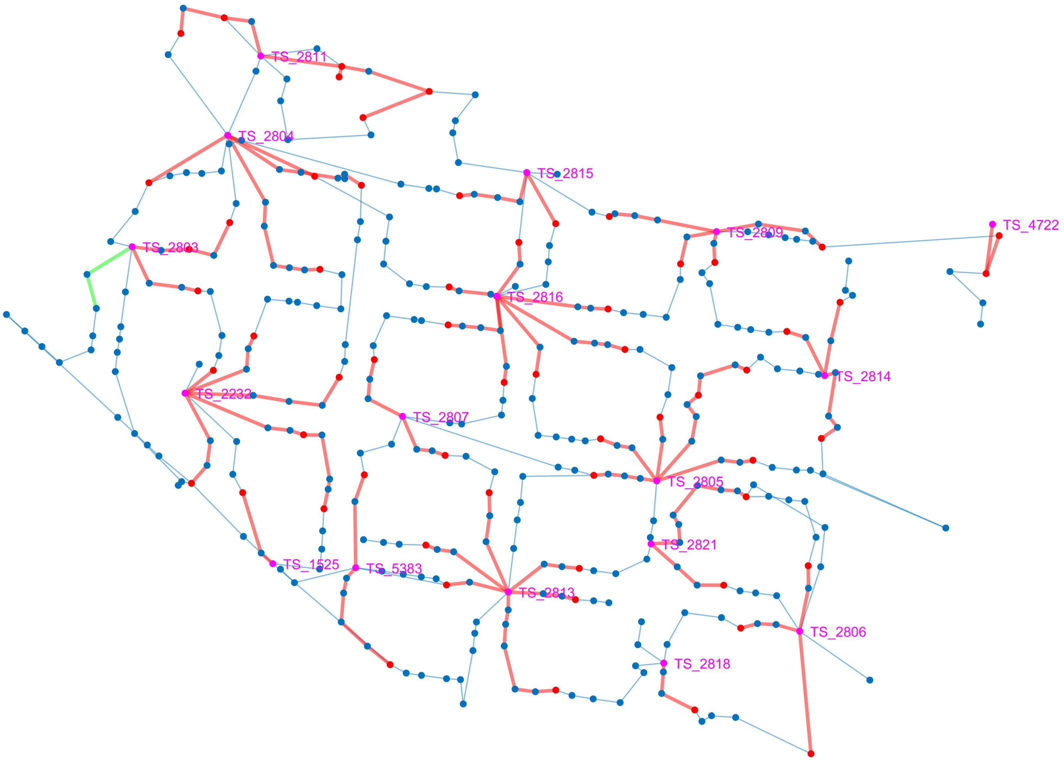

Figure 32: Vinohrady - Edges added (highlighted in green) to make all nodes at least in range of BPL

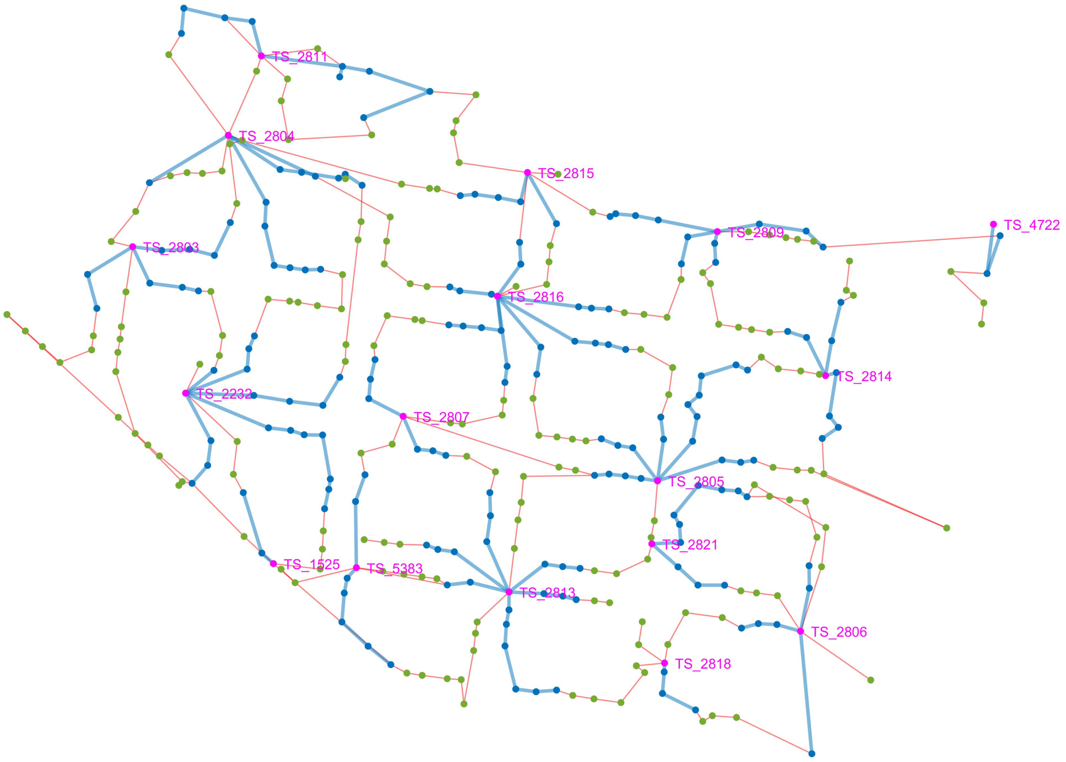

Figure 33: Vinohrady - BPL in combination with optical network resulting graph - edges not chosen (red), edges chosen for optical connection (blue), nodes directly connected to the optical network (blue, magenta), nodes with no direct connection to the optical network but in range of BPL (green)