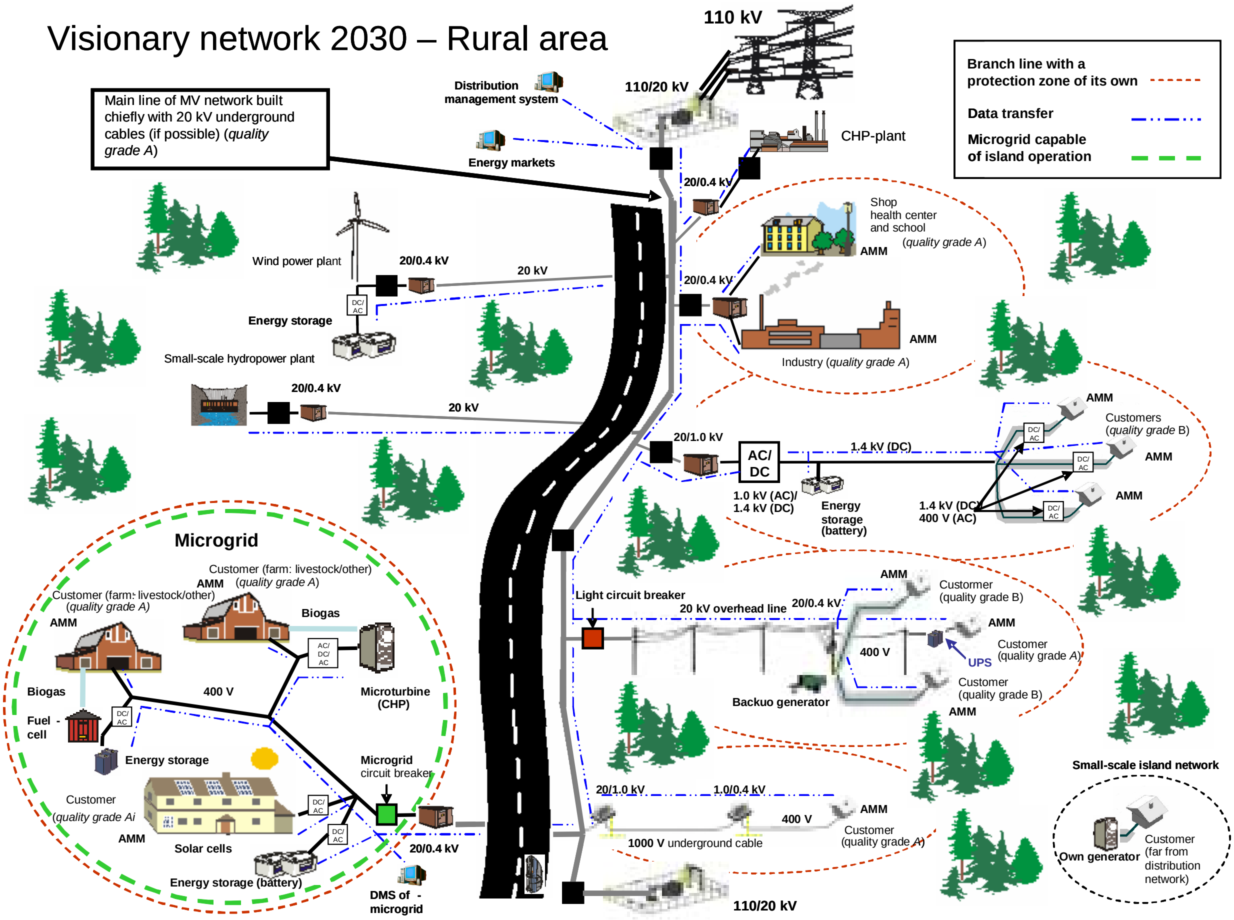

Distribution Network 2030

Vision of the

Future Power System

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Summary

The objective of this research was to create a long-term vision of the distribution network technology for the near future renovation, reinforcement and R&D needs. The present status of the network was discussed in brief, and scenarios were created for the changes in the operational environment and the technology available. An international view was taken to investigate the present solutions and future expectations in other countries.

Centralised power generation is supposed to prevail also in the future, yet distributed generation will play an increasingly important role; this process is hard to predict due to the uncertainty of the development of the regulation.

Higher reliability and safety during major faults are expected of the future networks at reasonable costs. Climate change and restrictions concerning the use of impregnants will cause problems especially for the overhead lines in forests. In rural networks, also ageing of the networks is a problem. For the urban networks, land use and environmental issues become more challenging, and reinforcement of networks is necessary due to the increased use of electricity.

There are several technical solutions available. As additions to the present technology, several new solutions were introduced. Important solutions in the future networks are supposed to be the wide range of underground cables, high-degree utilisation of communication and network automation solutions, considerably shorter protection zones and new layout solutions. In the long run, islanding enabled by the distributed energy systems and totally new network structures and solutions based on power electronics are supposed to improve the power quality and profitability. A policy decision on specific quality classes in network design is also supposed to be approved.

To achieve the targets set in the vision, also a Roadmap project is required. The project will coordinate and focus the development; this way, limited national resources can be utilised efficiently. Coordinated national development gives also a good basis for participating in international development and also for success of the Finnish technology industry

Confidentiality	Public

Espoo 27.05.2007

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Distribution :
Project group

Preface

The actors in the field considered a survey on the future perspectives of electricity distribution networks necessary. Asset management and a need for technical renovation of the distribution networks call for a long-term vision and an overview on the network technology and development opportunities. Since the life cycles of networks are typically several decades, today's investment decisions have very far-reaching effects.

To generate this vision, a Roadmap project directing and coordinating the development in the field was seen necessary to be able to efficiently take advantage of the national development resources. Coordinated national cooperation also creates conditions to influence the international development and to support the success opportunities of the Finnish technology industry.

The one-and-a-half-year project was funded and managed by the following collaborative partners: the Finnish Funding Agency of Technology and Innovation Tekes, ABB Oy, Ensto Sekko Oy, Fortum Sähkönsiirto Oy, Helsingin Energia, Oy Merinova Ab, Suur-Savon Sähkö Oy, SVK-pooli (a co-operative pool for the development of research activities in electric power engineering), Finnish Energy Industries, Vaasan Sähköverkko Oy, Vattenfall Verkko Oy, and the Technical Research Centre of Finland (VTT). The project was coordinated by VTT, the other research partners being Helsinki University of Technology (HUT), Lappeenranta University of Technology (LUT), Tampere University of Technology (TUT), and the University of Vaasa.

The project consisted of individual sub-studies, visits to foreign operators in the field, and numerous active workshops. In addition to researchers and professors working in the project, the following persons appeared as lecturers in the workshops: Aki Laurila (Fingrid Oyj), Markku Hyvärinen, Jussi Palola (HelenVerkko), Raili Alanen, Osmo Auvinen (VTT), Erkki Antila, Tapio Hakola (ABB), Juha-Heikki Etula (E.ON Finland Oyj), Ali Harlin, Hannu H. Kari, Erkki Lakervi (HUT), Markku Orpana (SiP Technologies Oy), Ilkka Halme (Parikkalan Valo Oy), Antti Pitkänen (JT-Millenium), Pertti Silventoinen (LUT), Juha Lohjala (Suur-Savon Sähkö Oy), Kimmo Kivikko, Terttu Pakarinen, Sami Repo, Heikki Tuusa, Seppo Valkealahti (TUT), Veli-Pekka Nurmi (the State Provincial Office of Western Finland), Tapio Potila (Eltel Networks Oy), Matti Jauhiainen (the National Emergency Supply Agency), Markku Vänskä (Vattenfall Verkko Oy), Jyrki Luukkanen (Finland Futures Research Centre, Turku School of Economics), Aimo Rinta-Opas (Koillis-Satakunnan Sähkö Oy), Hannu Katajamäki (the University of Vaasa), and Philip Lewis (VaasaEmg).

We express our thanks to all persons and organisations in the project for their valuable contribution and effort. Special thanks to Hanna Niemelä (LUT) for English translation based on document *Alue- ja jakeluverkkojen teknologiavisio 2030, Verkkovisio*. Espoo 2006. VTT Tiedotteita – Research Notes 2361. 89 p. (in Finnish), and Esa Pekkola for editoral help.

Authors

Abstract

The research objective was to create a long-term vision for the electricity distribution network technology to be applied in the rebuilding and R&D efforts required in the near future. The present state of the grid was briefly reviewed, and scenarios for changes in the operational environment and the available technology were created. An international view was taken to get acquainted with the present solutions and future expectations in other countries.

Centralised power generation is supposed to form the majority of energy production; however, also distributed generation will play an increasingly important role, which is hard to predict due to the uncertainty of the development of regulation.

Higher reliability and safety during major faults are expected of the future network with reasonable costs. The impact of the climate change and restrictions concerning the use of impregnants bring difficulties especially to the overhead lines in forests. In rural networks, also the ageing of networks is a problem. For urban networks, the land usage and environmental issues will be a growing challenge, and network reinforcements will be necessary due to the increased consumption of electricity.

To this end, the research project provides a set of technical solutions. In addition to the existing technology, a variety of new solutions are introduced. Important solutions in the future network are supposed to be large-scale application of underground cabling, high-degree utilisation of the communication and network automation solutions, considerably larger number of protection zones and new layout solutions. In the long-term, islanding enabled by the distributed energy systems together with totally new network structures and solutions based on power electronics are supposed to improve the power quality and profitability. A policy decision on specific quality classes in network design is also supposed to be approved.

To achieve the vision, a Roadmap project to direct the future development in the field was considered necessary in order to efficiently take advantage of the limited national development resources. Coordinated national development work also provides a good basis for participation in international development work and promotes the success of the Finnish technology industry.

Contents

1. Introduction

1.1 Starting points and objectives of the survey

The planning of the research project started from the view that the ageing of electricity distribution networks and the tightened reliability requirements have created a need for a large-scale renovation of the networks. Since the lifetimes of networks are extremely long and the present technology cannot provide the desired performance, a long-term vision and an overall view of the distribution network technology is required in order to correctly direct the investments in the future.

In the survey, it was found important to generate scenarios for changes in the operational environment, since the technical solutions concerning the distribution networks are made based on the requirements set on them. Equally, the international perspective was emphasised. The target was to investigate network solutions already applied in other countries and also visions for future technical solutions.

One of the aims of the project was to develop a methodological platform to objectively assess the applicability of various new technology solutions and to recognise the strategic development needs in different technologies.

Among the key objectives of the project was also assessing the need for a larger-scale collaborative research arrangement. Based on the Distribution Network 2030 project, for future purposes, it is possible to establish an extensive research project collaboration networking numerous research units and industry as a joint Roadmap project.

1.2 Funding and implementation of the research

The research was implemented as a Tekes project, coordinated by VTT. Other collaborative research partners were Lappeenranta University of Technology, Tampere University of Technology, Helsinki University of Technology, and the University of Vaasa.

The project was funded, in addition to Tekes, by ABB Oy, Ensto Sekko Oy, Fortum Sähkönsiirto Oy, Helsingin Energia, Oy Merinova Ab, Suur-Savon Sähkö Oy, SVK-pooli, Energiateollisuus ry, Vaasan Sähköverkko Oy, Vattenfall Verkko Oy, and VTT.

The project management group is introduced in Table 1.1, and the persons in charge at the universities are listed in Table 1.2.

Table 1.1. Project management group.

Name	**Organisation**
Erkki Antila (Chair)	ABB Oy
Jari Eklund	Tekes
Kari Noponen	Vattenfall Verkko Oy
Juha Lohjala	Suur-Savon Sähkö Oy (Savon Voima, Pohjois-Karjalan Sähkö, Kymenlaakson Sähkö)
Juha Rintamäki	Vaasan Sähköverkko Oy
Kari Luoma	Oy Merinova AB
Osmo Huhtala	Fortum Sähkönsiirto Oy and SVK pool
Taisto Lehonmaa	Suomen Energia-Urakointi Oy
Markku Hyvärinen	Helsingin Energia
Tuomas Antikainen	Ensto Sekko Oy
Elina Lehtomäki	Energiateollisuus ry
Lauri Kumpulainen (Research Coordinator)	VTT (acted also as the representative of the universities in the management group)

Table 1.2. Persons in charge of the project at the universities.

Matti Lehtonen	HUT, Helsinki University of Technology
Jarmo Partanen	LUT, Lappeenranta University of Technology
Pekka Verho	TUT, Tampere University of Technology
Kimmo Kauhaniemi	University of Vaasa

Essential methods in the research were workshops and excursions abroad. The countries visited were Germany, Sweden, the USA, Canada, and Ireland. Workshops were arranged in Vaasa, Tampere, Lappeenranta, and Espoo with 40 to 80 participants in each workshop.

2. Present state of the Finnish distribution networks

2.1 General

The assessment of the present state of the networks was made based on interviews and a literature survey. In total, 15 representatives of the distribution companies or network construction companies were interviewed. The problems in rural networks and urban networks are clearly different from each other.

2.2 Distribution networks in rural areas

Considering rural distribution networks, as expected, two main problems emerged:

1. Medium-voltage overhead lines, particularly when located in forests, are highly susceptible to faults, and the system's susceptibility to a common cause failure as a consequence of storms is significant.
2. Most of the medium-voltage lines have been built 30–50 years ago, and as a result, a large number of poles are now ageing.

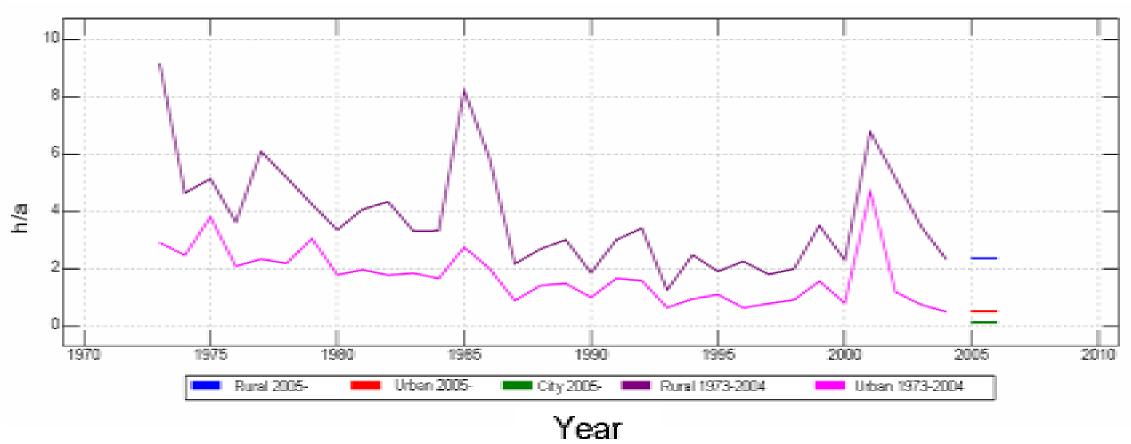

Figure 2.1. Development of average outage duration from 1972 to 2005 (Finnish Energy Industries 2006)

2.3 Urban distribution networks

The load growth varies in urbanised areas; there are areas of noticeable load growth, but also areas where the situation has stabilised. The only electrotechnical problem that clearly emerged in the survey was the need for improved transmission capacity resulting from the load growth. At present, more topical problems are the challenges related to environmental issues, in particular the problems in space utilisation. Also other environmental effects of distribution networks are gaining significance in urban environments. A new challenge in urban networks is the increase in cooling load and the resulting need to improve the cooling of distribution substations. This tendency can also be seen particularly in the centres of large cities by a load peak in summer, when the cooling conditions of the transformers are at their worst.

The need for a large-scale renovation of urban networks due to the ageing will emerge later than in the rural networks. Further, in the areas of rapid and constant load growth (in growth centres), the network is renewed in any case largely as a result of growth. However, there is not enough information on the real lifetime of network components so far. The life cycles of primary and secondary network components and information systems differ considerably from each other.

2.4 Regional networks

No major topical problems were detected in regional networks, if we exclude the external demands placed on the lines and other network structures. Being tree-proof, that is, secured against risks caused by trees (e.g. by trimming and clearing of line paths), the lines have proven to be reliable, similarly as the primary substations. On the other hand, the ageing of the main transformers is considered to lead to increased risks. Problems in land usage and the emphasised environmental issues will hamper the construction of new connections, but also the existing lines are facing certain threats.

The constant load growth can be seen also in the regional networks. The loads are growing both in growth centres and in rural areas. Although the proportion of permanent residents is declining in rural areas, the increasing number of holiday homes leads to load growth. Difficulties in anticipating the future location of electricity generation systems and the forms of production have brought an element of uncertainty into the persistent development of transmission networks.

2.5 International reliability comparisons

International reliability comparison studies based on statistics (cf. Heggset et al. 2004, Singh 2005, and Kjølle 2006), give the following information on the state of the Finnish distribution networks:

- At present, the reliability of supply is, at the most, of average level in Europe.
- The annual variation in the reliability reveals the susceptibility of the Finnish distribution networks to climatic disturbances.
- In Finland, the protection zones are typically large, and therefore a disturbance caused by an individual fault is seen in a very large area. Usually the protection of feeders is fully concentrated to the primary substation.

Figure 2.2 illustrates the Nordic reliability comparison of the distribution network.

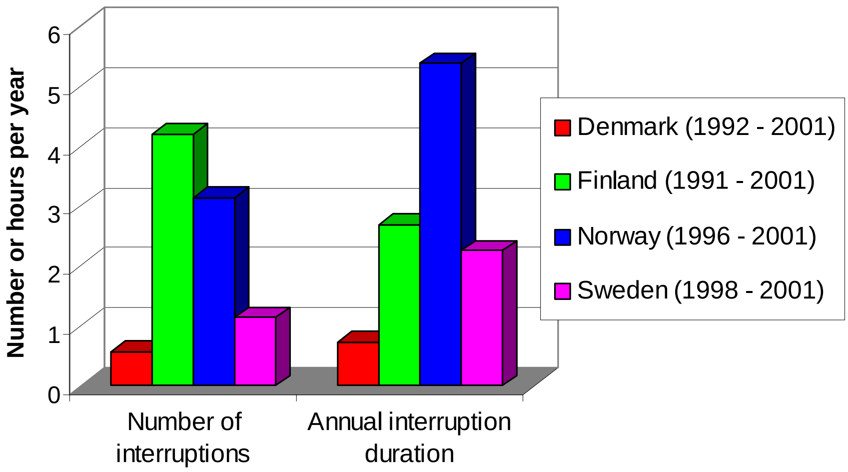

Figure 2.2. Comparison of outage rates and durations in the Nordic countries (Kjølle 2006).

3. Solutions and visions in other countries

In the analysis of distribution networks in other countries, the solutions relevant from the Finnish perspective are investigated. The results of this section are discussed in more detail in a separate report (Lågland 2006).

The following visions and technology road maps in other countries were included in the survey:

- Sweden, Elforsk: Vision 21. Electrical industry's vision of the future electricity transmission and distribution system.
- Sweden, Elforsk: Ett uthålligt elsystem för Sverige. Forecasting the development of the power industry, technologies, and methods for electricity generation.
- Norway, SINTEF: Distribution 2020. Fault handling and integration of distributed generation in MV networks, protection strategies.
- USA, National Rural Electric Cooperative Association: Electric Cooperative Technology Solutions. Low-cost electricity distribution, reliability, fast responding, sustainable solutions, quality of life.
- USA, Electric Power Research Institute: Electricity Technology Roadmap. Architecture for the electricity distribution network of the future.
- EU, European Commission Directorate General for Research: Technology Platform for the Electricity Networks of the Future.
- Canada, Capgemini and CEA Technologies Inc.: Electric Distribution Utility Roadmap. Factors of the future development and topics common for the future distribution companies.
- USA, National Electric Delivery Technologies: National Electric Delivery Technologies Roadmap.

At the moment, expectations are high for instance on the following technologies, the R&D of which is strongly invested in: intelligence, information technology, high-temperature superconductivity and hydrogen technology. In the field of network technology, protection, automation, power electronics, micro grids, fast simulation, and modelling are the present areas of emphasis. In the production, focus of attention is on the expanding production portfolio and the integration of distributed generation and energy storages. The research on network solutions has concentrated on simple networks without redundancy, networks with built-in redundancy, hybrid networks, and micro grids.

The report (Lågland 2006), in which the results are discussed in more detail comprises four parts:

Current foreign network solutions

- Solutions in the development and pilot phases
- Visions and visionary distribution systems
- Technologies applicable to Finland

In the following, some present or future technical solutions applicable to Finland are discussed in brief; these solutions are either already in use elsewhere, or they are in the pilot phase or under research, or they have been inspired by some technology applied in other countries.

In many countries, the unfavourable development of the key figures associated with the supply reliability is partly due to an increase in exceptional natural phenomena. On the other hand, the opening electricity markets have created pressure to increase the utilization ratio of network components and systems. Also the utilization ratio of intelligent devices, the state of which can be monitored, can be increased. However, an increase in the load and utilisation ratio also has to lead to an increased utilisation of backup supply connections at the medium-voltage level to guarantee the electricity supply also in fault situations. When raising the utilization ratio of the network, the network type and configuration have to be reconsidered, which in practice means for instance adding switchgear to the network.

3.1 Intelligent components and systems

Intelligence in components and systems enables the state control and optimisation of the system. Intelligent components are for instance self-protected distribution transformers, intelligent fuses, intelligent transformers, and intelligent customer connections. Intelligent systems mentioned in the visions are for instance a self-healing power network, intelligent distribution system, smart grid, and intelligent measuring.

For instance EPRI is applying for a patent on the concept of intelligent universal transformer, IUT (EPRI 2006). An intelligent transformer is modular, all-solid-state switching device comprised of IGBT components and characterised by:

- regulation of both voltage and power factor
- conversion from AC single-phase supply to DC supply, 400 Hz AC supply or normal three-phase supply
- power quality enhancement
- operation as a multifunctional node and a sensor in condition monitoring of the electricity distribution system
- reduced need for spare parts thanks to modularity
- no harmful liquids

The design of an intelligent transformer concept was commenced in 2004. A report on the final design and product specification of the transformer is to be published in 2008 (EPRI 2006).

A smart grid is defined in Spirae (2006) as follows:

The name "Smart Grid" refers to a transformed electric power system that closely integrates the supply and demand sides of the electricity business with advanced communication, information, and control technologies.

In practice, enhancing the intelligence of an electricity distribution network means seamless integration of a large number of different functions and components into a single unit. This sets specific requirements for the technologies to be applied and particularly for the communication between different parts of the system. In respect of the communication, the Standard IEC 61850 forms the base for the implementation of a smart grid (Antila 2006).

In Finland, considering intelligent systems, the EU SmartGrids Technology Platform is of key importance. The lifetime of distribution networks is very long, and the related technology is developing quite rapidly; therefore it is difficult to take all the future development trends into account in the network construction. Consequently, the most important requirement set for the networks is their flexibility. According to the EU SmartGrids Platform, flexibility is reached with correct technical solutions, interfaces, intelligence, and open environment (Table 3.1).

Table 3.1. Cornerstones of the future smart grids.

FLEXIBILITY			
Technology	**Interface**	**Open environment**	**Intelligence**
Network structure Fault management Quality of supply Distributed generation Energy storage	Power electronics	Harmonisation Standardisation Legislation	Information systems Telecommunications systems Protection systems

3.2 Sectionalisation as a means to improve protection and reliability of supply

Sectionalisation refers to a method in which a feeder is provided with switchgear to isolate the faulted network section, and consequently, to minimise the feeder section left without supply. In addition to the fact that sectionalisation limits the scope of a supply outage by minimising the number or customers out of supply, it is often necessary also because of the requirements set for adequate network protection.

3.2.1 Benefits of sectionalisation in protection

A main line can be divided into two or more zones by reclosers or circuit breakers with reclosing capability (Figure 3.1). In addition to the indices characterising the average interruption frequency (SAIFI) and interruption duration (SAIDI), a recloser also improves MAIFI, an index indicating the momentary interruption frequency, since faults in the receiving end of the line do not cause reclosings in the supplying end. Adding the first recloser brings the largest benefit, amounting theoretically to a 25 % improvement in SAIFI and SAIDI.

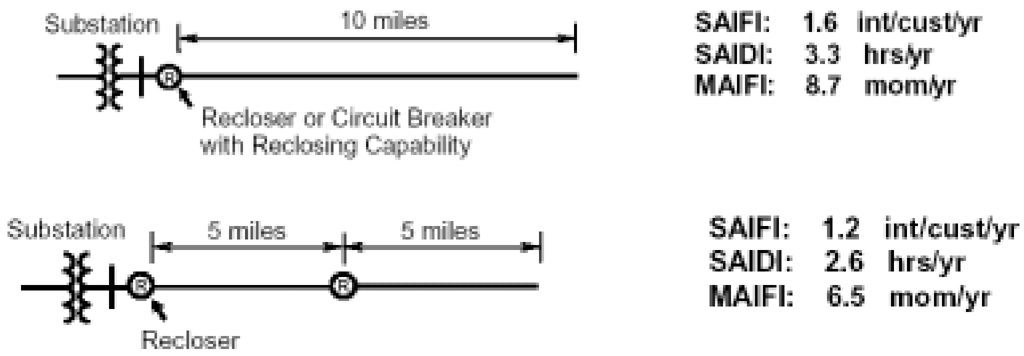

Figure 3.1. Sectionalisation of a main line; effects on the reliability indices (ABB).

An inherent way to add zones to the network is to separate the branch lines as zones of their own (Figure 3.2). Branch lines from 20 kV main lines can also be built with 1000 V technology, in which case the branch line and its protection forms a protection zone of its own thus preventing a fault in the branch line from affecting the rest of the network (Figure 3.2a, Lohjala 2005).

Also by applying a SWER (single wire earth return) system, the branch lines can be protected separately by fuses and with a recloser and relay/fault indicator (Figure 3.2b).

When the branch line is equipped with a switch disconnector and fault indicator, the switch disconnector can isolate a faulted branch line when the recloser on the main line is open (Figure 3.2c). In this case however, an interruption will occur also on the main line. A better result will be reached with a recloser on the branch line. With a relay or fault indicator, a recloser in the branch line can isolate the faulted branch (Figures 3.2d and e).

A solution of particular interest is a semiconductor switch (recloser) on a branch line (Figure 3.2 f). At present, the power-electronic semiconductor devices are reaching the performance level required for this purpose, especially when the fault currents far downstream from the primary substation are usually relatively low. However, a visible clearance between open contacts is probably required for safety reasons. This can be provided by a simple disconnector that operates only when necessary and is slower than the actual circuit breaker element. The opening of a semiconductor switch is about 50 ms faster than that of a traditional one, and thus, reasonably good protection tripping times in the entire feeder can be achieved. In the 1000 V low-voltage system, a semiconductor switch can be said to be a feasible solution already at present.

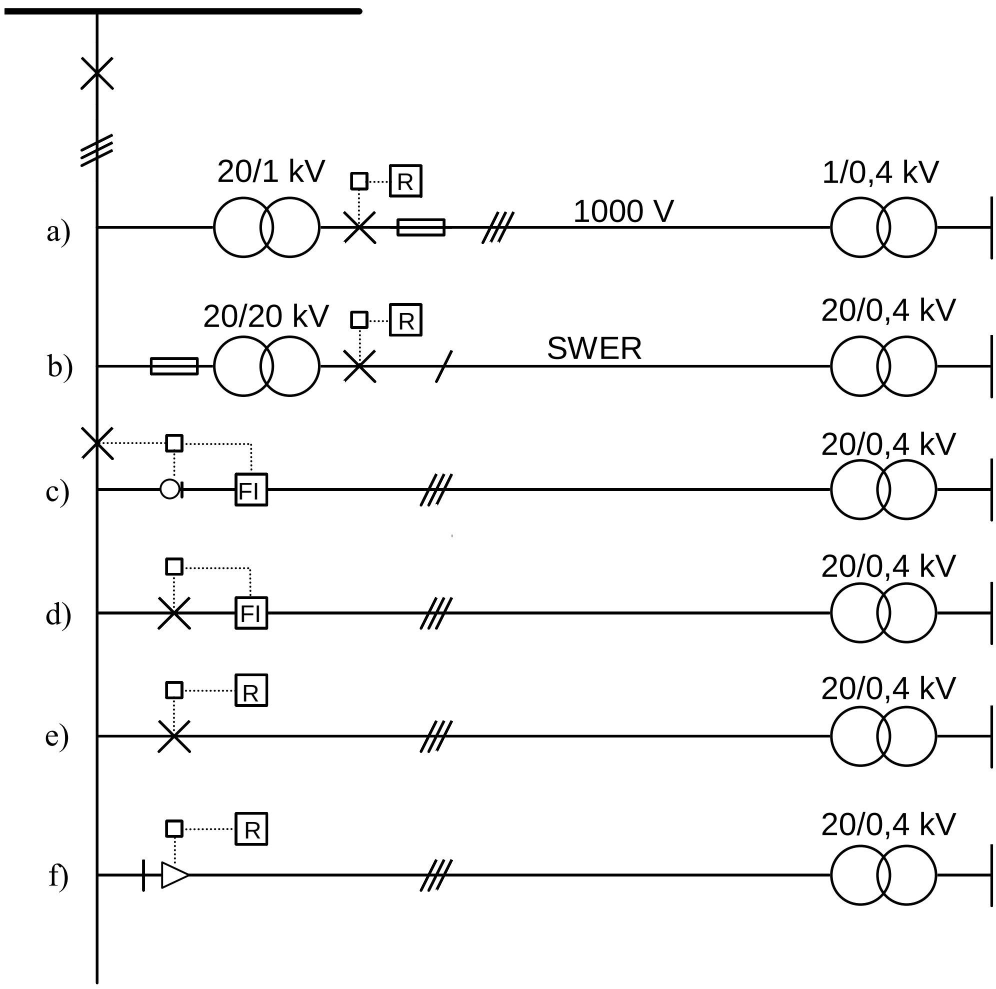

Figure 3.2. Alternatives to improve the reliability of medium-voltage lines by the sectionalisation of branch lines.

3.2.2 Fault management

Based on the results of the questionnaire survey by the CIRED Working Group WG03 (1998) (Asmuth et al. 2005), the level of automation has been compared in the countries participating in the survey (Figure 3.3). The result supports the view of low utilisation of local network automation and combined remote control and local automation in the Finnish distribution networks. This may be a conscious choice to simplify the network management, yet here lies also an opportunity to further improve the power quality.

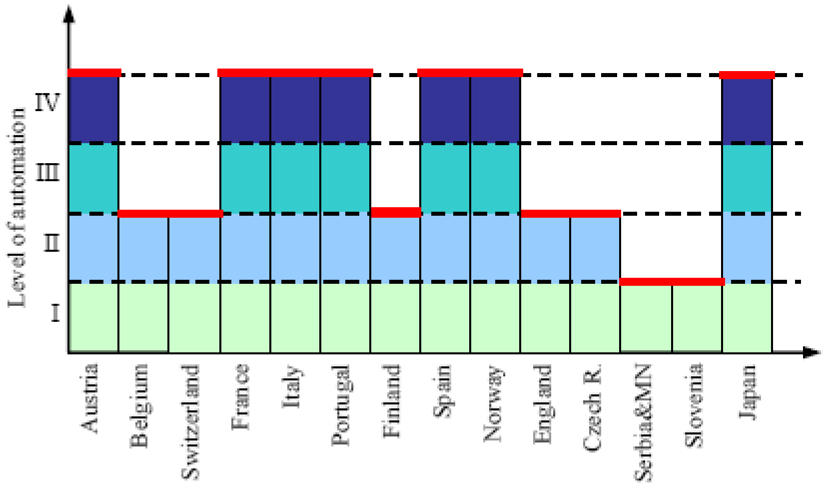

Figure 3.3. Level of automation in some countries. Levels: I=Fault detectors with local and/or remote indication, II=Remote control of switchgears, remote indication and remote measurements, III=Application of local automation (reclosers, autosectionalisers, changeovers), IV=Combination of remote control and local automation. (Popović, D., Glamočić, L., Nimrihter, M., Tanasković, M., Vukotić, D., Damljanović, D. Optimal automation level of medium voltage distribution network. 18th International Conference on Electricity Distribution (CIRED), Turin, 6-9 June 2005.)

According to a survey conducted in the USA, load rates have increased notably from the 1970s onwards. If the load rate of the network components is increased, the number of backup connections has to be increased accordingly, which also brings more automation to the network.

The medium-voltage network automation minimises the effects of faults and interruptions with respect to the area and duration. The network automation could be based on the control of reclosers and disconnectors (autosectionalisers) at the distribution substations located at points of strategic importance for the network management. Network automation is a particularly efficient way to improve the availability of electricity distribution in rural areas, yet there are potential application targets also in population centres.

3.3 Underground cabling

3.3.1 Increasing the rate of undergrounding

The EU countries increase underground cabling in their low- and medium-voltage networks (Tables 3.2–3.3). The target is to change over to underground cables at least in network sections vulnerable to weather conditions to improve the reliability of supply in Europe (EC 2003). In Finland, the total length of medium-voltage network is ca. 140 000 km, of which 10 % is built with underground cables (in 2003). Correspondingly, the total length of low-voltage network in Finland is ca. 215 000 km, of which underground cables account for 30 % (in 2003).

Table 3.2. Low-voltage network lengths and rates of undergrounding in some European countries (EC 2003).

	Km of network	Length of network (m/habitant)	Percentage underground	Rate of undergrounding/year in the period 1999/2000	
				Km/year	%
Netherlands	145.000	8,9	100 %		
UK	377.000	6,4	81 %	9.000	1,4
Germany	926.000	11,3	75 %	40.000	4,3
Denmark	92.000	17,6	65 %		
Belgium	108.000	10,6	44 %		
Norway	185.000	41,3	38 %		
Italy	709.000	12,1	30 %	11.000	1,6
France	632.000	10,5	27 %	20.000	3,1
Portugal	112.000	11,9	19 %		
Spain	241.000	6,0	17 %		
Austria	65.000	8,0	15 %		

Table 3.3. Medium-voltage network lengths and rates of undergrounding in some European countries (EC 2003).

	Km of network	Length of network (m/habitant)	Percentage underground	Rate of undergrounding/year in 1999/2000	
				Km/year	%
Netherlands	101 900	8,9	100 %	2 000	2,0
Belgium	65 000	6,4	85 %	2 000	3,0
UK	372 000	6,3	81 %	5 200	1,4
Germany	475 000	5,8	60 %	12 000	2,5
Denmark	55 000	10,5	59 %		
Sweden	98 700	12,3	53 %		
Italy	331 000	5,7	35 %	5 100	1,5
France	574 000	9,5	32 %	8 000	1,4
Norway	92 000	20,5	31 %		
Spain	96.448	2,4	30 %		
Portugal	58 000	6,1	16 %	950	1,6
Austria	57 000	7,0	15 %		

3.3.2 New technical solutions required by cable network

In rural areas, underground cable network configurations are often urban network solutions. By optimising the existing underground network structures and components for a lower load density, costs can be optimised; this can be done for instance by modulating and selecting suitable network alternatives and solutions applicable to cable ploughing.

New solutions are required also in rural cable networks, such as pole-mounted distribution substations installed at the pole foot, medium-voltage cable distribution cabinets, medium-voltage RMUs and light distribution substations.

Also distribution substations have been developed further by integrating and adding new functions to them. An interesting example is the Transfix distribution substation with integrated protection and disconnection functions. The substation can also be provided with compensation equipment for local compensation.

In addition to distribution substations, also the underground cable network requires additional new solutions for instance for the compensation of high capacitive earth-fault currents in the cable network, network branching, voltage isolation, voltage measurement, network earthing and backup supply arrangements.

Staffanstorps Energi by the city of Malmö in South Sweden has decided to entirely change over to underground cable networks and has therefore developed a maintenance-free modular cable network according to the overhead network model. The distribution system consists of a ploughed-in underground cable network or an aerial cable network with hot-galvanised steel poles, a compensation system based on centralised and local earth-fault current compensation, an oil-filled Elastimold branching module, nitrogen-filled Elastimold disconnector module (sectionalising element) provided with an isolating distance, 50-315 kVA screened plug-in-type modular distribution substation and backup power generation unit adapted to the modular system. During supply outages, a mobile backup supply generator unit is employed for island operation of the network.

The earth fault currents in the underground network in Staffanstorps Energi are compensated both centralised and locally (Figure 3.4). Local compensation equipment is located at the distribution substations.

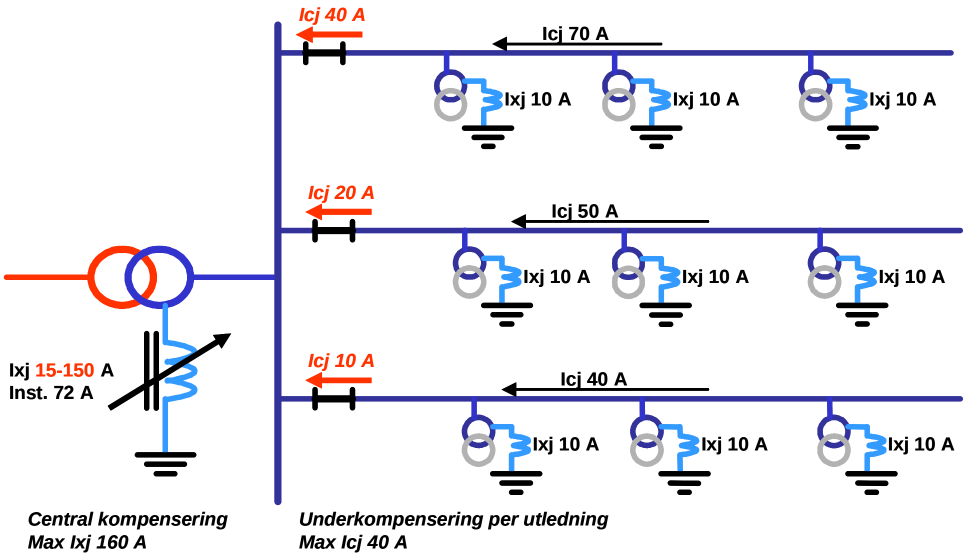

Figure 3.4. Earth fault current compensation system in the underground cable network, Staffanstorps Energi (22 kV, max Icj=500 A) [9]. (Göransson, O., Ny förenklad distributionsteknik sänker totalkostnaderna. Framtidens robusta och kostnadseffektiva elnät, Seminarium 17.1.2006. KTH, Stockholm.)

3.3.3 Light cable network in rural distribution

As the undergrounding rate and the load density in rural areas are increasing, the network structural solutions approach urban network structures. Such solutions are for instance underground cabling, distribution substation solutions and various integrated and modular solutions. These well-proven solutions can be applied also to overhead line networks; good examples are the RMU of overhead line networks and plug-in termination technology. As the load density is increasing and the reliability of supply is emphasised, also other network configurations become competitive alternatives. A network configuration worth considering is a satellite network, investigated and developed since the 1970s and applied in Denmark, Norway, and Sweden. Pioneering network companies have been for instance Bergen Lysverker in Norway and Skellefteå Kraft and Kungälvs Elverk in Sweden, although this network type has been selected by other utilities also. The applicability of a satellite network configuration in rural areas is based on the following factors:

- Investment costs are 5–15 % lower than in a conventional cable network
- Distribution transformer power capacities in the satellite network are of the same scale as for the transformers in the overhead line networks
- Power losses are lower than in a conventional cable network
- Key figures of the supply reliability are of the same scale as in a conventional cable network, yet notably better than in an overhead line network
- Satellite network configuration can be used both to expand an existing network or to construct a new one
- It can be used together with other network systems
- Satellite network is a very flexible network configuration

Satellite network configurations are in use also in Finland, and they are a relevant subject of study when considering network solutions suitable for wider application.

3.3.4 Network

In urban areas, it is difficult to cost-efficiently increase the reliability of supply any further. Nevertheless, already with two medium-voltage feeders, the supply reliability can probably be raised to a new level; this may be realistic in the centres of large cities.

A network solution of this type is the Network distribution system used in large cities in North America (see Figure 3.5). A Network system comprises radial medium-voltage feeders that supply a meshed low-voltage network with distribution transformers. As the low-voltage network is supplied by several transformers or medium-voltage feeders, it has to be ensured that the low-voltage network does not continue to supply a faulted transformer or a medium-voltage network section. For this purpose, a device known in the USA as ”Network protector” has been developed. The device is an air circuit breaker, which is tripped open by a fault on the supply side, and which is able to automatically restore supply when energised again or the fault situation is over. With the device, a single transformer or medium-voltage network fault is isolated quickly from the network and it does not lead to an interruption in the low-voltage side.

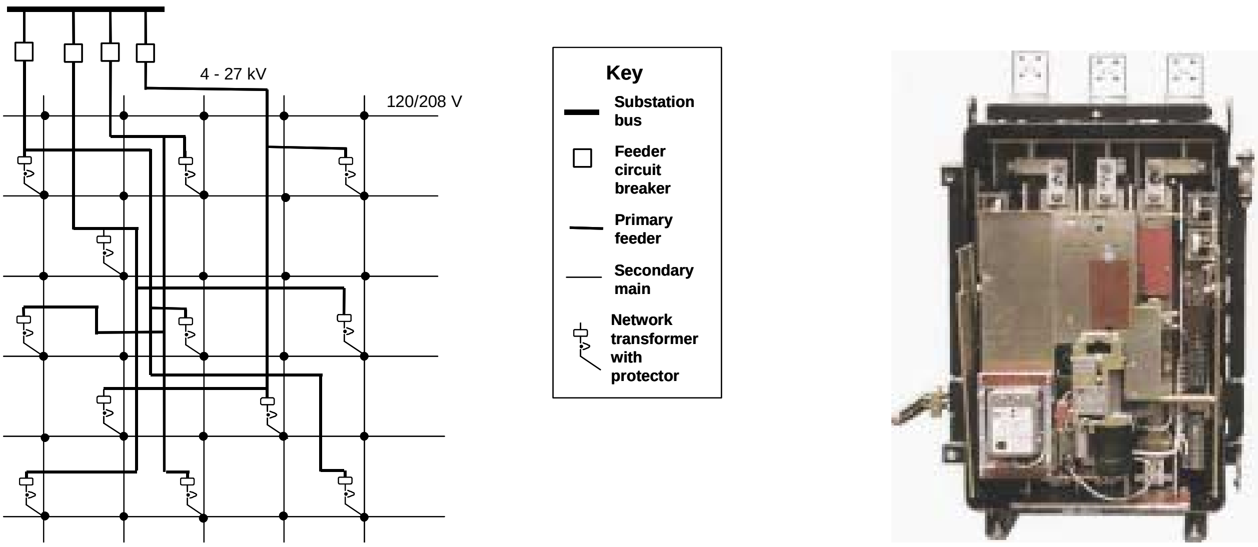

Figure 3.5. Network distribution system and Network protector (Freeman et al. 2005).

4. Operational environment scenarios

Among the objectives of the Distribution Network 2030 project was to consider the change in the operational environment from a wide perspective and to create scenarios for a visionary network. The changing global environment was taken into account at some level already in the preparation of the project, but the workshops in Vaasa and Tampere in 2005 went deeper into the subject in their presentations, group works and individual considerations.

When considering changes in the operational environment from a wide perspective, futures research provides a rational framework for the analysis. Futures research is a multi-disciplinary field that aims at envisioning and analysing different future trends and scenarios, *alternative futures*, by combining observations made in various other disciplines; the aim is thus not to provide a single vision or forecast of the future. Unlike other disciplines, futures research takes values into account as factors guiding the choices; futures research also participates in ”making the future”, in other words, it can influence decision-making.

Scenario work, as many other methods applied in futures research, is based on the analysis of changes in the operational environment. Often, the starting point is to find megatrends common to all fields of activity, which cannot be significantly influenced by the field to be observed. In the field-specific analysis, the focus has to be on the forces driving towards change and on the opportunities to affect these forces. It is also important to be able to distinguish the permanences, that is, the basic beliefs in the field. In the scenario method, the analysis of the change in the operational environment serves as initial information when creating various future scenarios. Scenarios are well-founded stories of future; typically more than one story is created. An often-applied method in scenario work is to compile a fourfold table for the alternative developments of two significant driving forces. The fourfold table produces four scenarios, which can be utilised in many ways in the strategy work. We may choose a probable scenario and act according to it, or we may select a strategy that works in all scenarios. Further, we may decide on the best scenario and begin its active implementation. The Visionary Network represents, in a way, the latter option: the entire industry aims at choosing the best scenario and begins to implement it as a unity. However, the project has not generated a single universal scenario set by the means of scenario work, but rather several exemplary scenarios related to the electricity distribution. This chapter introduces some views based on forecasts and estimates on the possible development trends and extracts some change factors relevant for the scenario and vision work to be applied to in the fourfold table; also some examples are given of these factors and trends.

4.1 Scenarios related to the development of society

From the perspective of electricity distribution, the key factor related to the societal development has probably been the change in the community structure. In the case of centralised development, the electricity supply per customer becomes more and more expensive in declining areas compared with growth areas. An equal treatment of electricity consumers within a distribution company becomes therefore increasingly a form of indirect regional policy, the retention of which may not necessarily remain generally acceptable. In addition to political issues, the development of the community structure depends on choices made by individual people: is the trend towards living in the countryside, and how much are we ready to pay for it? A significant increase in the number of holiday homes indicates this trend; the improved opportunities for remote work create favourable conditions for this development. Figure 4.1 illustrates a fourfold table of alternative scenarios.

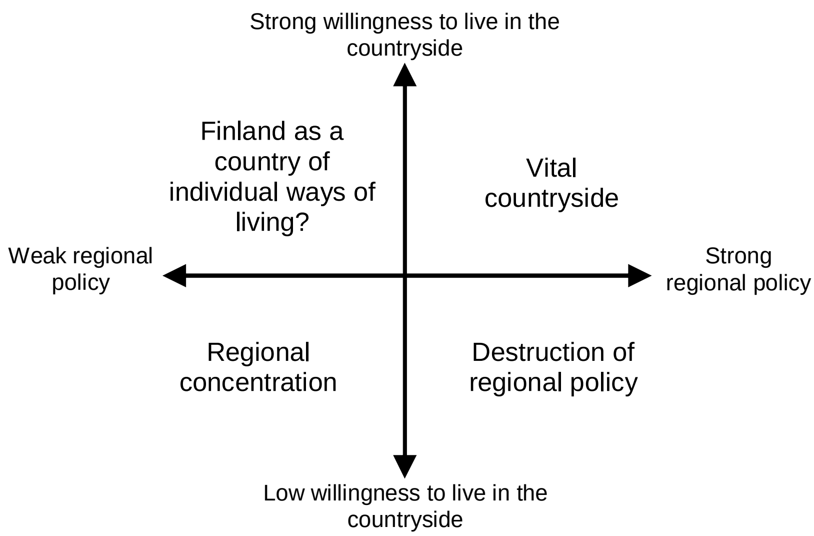

Figure 4.1. Scenarios for the community structure.

The suggested scenarios are neither definite nor exclusive, but rather provide a description of the possible development in different circumstances. The two dimensions of the scenarios are also not independent, since regional policy is a part of democracy, which is guided by the voters' views and choices. From the electricity distribution point of view, the right top corner, that is, a vital countryside would be closest to the present situation. Concentrated regional development could lead to a situation in which equal treatment of citizens is abandoned, which in turn would accelerate concentrated regional development and degrade the supply of electricity in declining areas. Instead, the alternative of a Finland with individual ways of living could well lead to local energy generation and dismantling of networks.

4.2 Energy production scenarios from the perspective of electricity distribution

The future energy generation methods are influenced by the technology development, the energy price increase, the need to control the climate change and political decisions (e.g. on the energy saving objectives and the support to production methods based on renewable energy sources).

The energy production scenarios also affect the development of transmission and distribution networks. According to forecasts, the annual consumption of electrical energy and thereby also power generation will constantly increase also in the future. As the price of energy will rise, the variety of alternative forms of energy generation will grow. Renewable energy sources, such as wind and biofuels will gain ground; they will be significant in rural areas in particular, where land usage (wind farms) and air quality (emissions from burning wood fuel) do not set restrictions or create a major cost burden. Considering the electricity distribution networks, small-scale electricity generation may lead to a reduction in power transmission. Proportionally, the amount of transferred energy will decrease more than the peak power. Despite increased wind power and distributed generation, it is likely that we will still have a strongly centralised power system, in which the networks have a key role. In fact, an increase in distributed generation seems rather to impose further requirements on the network. Connecting distributed generation to the network and the management of a network including distributed generation may lead to a significant increase in the electricity distribution costs.

In the long term, the development in electrical energy storages may have a strong impact on the construction of distribution networks. An energy storage could be utilised to even out load peaks, which would bring a decrease in the peak power of the network. The development of electrical energy storages opens up opportunities for the wider use of electric cars. At present, transport accounts for 17 % of the total energy consumption in Finland, which corresponds to the amount of energy generated by nuclear power. If the electric cars and plug-in hybrid cars become more common, also charging of batteries will strongly increase the network load. In the long term, the development in fuel cell technology and its application to vehicles may lead to a situation in which the fuel cells of cars generate electricity to the network while the cars are parked.

The advance in the energy solutions for transport may enhance the competitiveness of fuel cells also in individual houses. An alternative to a fuel cell in an individual building is a fuel cell shared for instance by a village. A catalyst in the development can be the possible abandoning of the point stamp tariff system (equal prices regardless of the location of the customer). A decisive factor is also the development of building heating systems in rural areas. Most of the owners of oil-heating systems have to find alternative heating solutions, which will have a significant impact on the electricity distribution. Such an alternative solution can be for instance a cogeneration system sized for the individual house, known as Micro-CHP (Combined Heat and Power).

The energy generation development trends also have an impact on the development of electricity transmission and distribution networks. According to forecasts, the consumption of electrical energy and thereby also generation will constantly increase. For various reasons, it is difficult to predict the amount of distributed generation and energy storages, and therefore it is likely that there will be notable differences between different networks in the future. The selected network solutions but also design, distribution management and automation systems should nevertheless be flexible also to rapid changes in the amount and direction of transferred energy.

4.3 Reliability of supply scenarios

Among the key factors guiding the development of electrical power networks is concern about power quality. Already at present, it is estimated in the U.S. that the expenditure caused by poor power quality accounts for 26 billion USD annually. Due to the increased application of various electrical drives, electronic control devices, and high-efficiency lighting installations, the line voltage quality is anticipated to degrade further. Simultaneously, the requirement for reliable and uninterrupted power supply is emphasised in the future. For instance, banking systems allow only a 30-second annual interruption time, while the maximum annual interruption time for hospitals and airports is about 5 minutes. The most critical load is online trade, which suffers significant damages already in the occurrence of an outage of 30 ms (Rabinowitz 2000).

In Finland, CENS values, costs of energy not supplied (outage costs) have been analysed in 1992 and last in 2005 (Silvast et al. 2005). During this period, the outage costs have approximately doubled. This trend can be expected to continue, and thus, during the reference period of the visionary network project, the outage costs are anticipated to double again.

A quite probable scenario related to the reliability of supply involves the tightening regulation. This would mean taking all interruptions into account as a part of the supervision and regulation of the electricity distribution business. In addition to short interruptions, also voltage sags may be incorporated in the regulation. Should this scenario come true, extensive and verifiable interruption statistics are required. This, however, is a challenging task, in particular, if in addition to average parameters, also the outage rates and durations of customers suffering most from the interruptions are controlled.

An alternative to the statistical data gathered by the authority could be data registers based on automatic meter reading and the compensation of interruptions in electricity bills. This becomes possible by new metering systems, and would require the definition of a national minimum level for compensation claims.

Both above-described scenarios imply that the quality of supply (interruptions, voltage) is chiefly achieved by actions focused on the distribution network. If the requirements are tightened and an equal treatment of customers remains as a basis of operation, significant investments on the reliability of networks will be necessary, which in turn will lead to higher distribution tariffs. However, most of the end-users are not ready for this, but the customers' requirements will be differentiated; in other words, some of the customers will require more reliable supply, while for some of the customers the quality is not a key issue. In that case, market-based quality may provide an alternative, the quality being now a price factor similarly as the traditional tariffs. Thus, instead of developing the whole network, an answer can be found in customer-specific local solutions, the costs of which are shared between the distribution company and the customer (market-based model) and which are supported by the development of distributed generation and power electronics.

A possible intermediate of the above two scenarios is the regional differentiation of reliability expectations. However, regional specifications should not be made based on the structure of the existing distribution network but on the basis of the community structure in the area; a possible basis could be for instance land use planning. In zoned urban areas, a higher reliability could be expected than outside these areas. In population centres, a very high reliability could be expected, that is, a weatherproof network, and short interruptions could be compensated for. In rural areas, the standard quality could be somewhat lower. A quality deviation would be compensated for in the electricity bill or it would be incorporated in the official supervision. Should a customer require better than standard quality supply, this has to be achieved by investing in local quality assurance. A scenario of this kind can be drawn by applying the fourfold table in Figure 4.2.

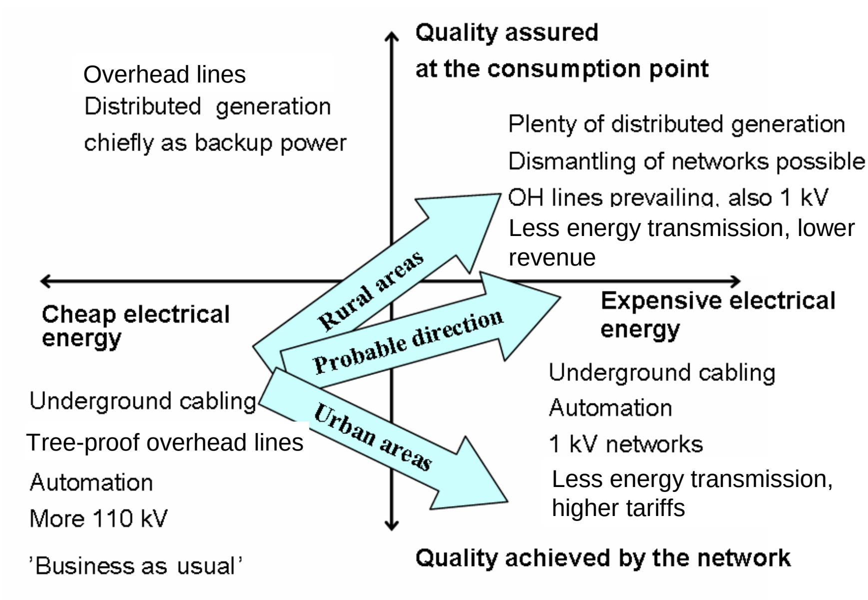

Figure 4.2. Four scenarios for the development of reliability.

4.4 Scenarios related to environmental issues and climate change

From the electricity distribution perspective, significant scenarios can include restrictions or prohibitions on the use of environmentally harmful substances. For instance, the use of impregnated wooden poles can be prohibited, or only an impregnating method by which the lifetime of the poles is notably shorter is allowed. Such a decision would require the use of alternative pole materials (steel, plastic, concrete), which may considerably increase the costs of overhead lines.

Also the requirements on the electric and magnetic fields caused by electricity distribution systems can be tightened. A relevant issue that has also to be followed up are the intentions to limit the use of SF_6 gas.

As the environmental consciousness is increasing, also ethical values are emphasised. This can be seen for instance in growing demands to better merge the electricity distribution system with the landscape, or even to hide it altogether. Also dealing with the issues of land use is becoming increasingly complicated, which delays for instance the construction of transmission lines. As the cities are growing further and they become more and more densely built, the issues of land use will have a significant impact on the network structure and cost level.

As a result of **climate change**, **windiness** and thunder storms in particular are considerably increasing. This in turn leads to a higher fault probability. Therefore, in visionary reliability analyses, the rate of faults caused by these climatic factors should be set to be for instance 1.5-fold compared with the present rates.

Precipitation is predicted to rise markedly in Finland; this softens the soil and degrades its strength. Soft soil hampers the maintenance of power lines and the operation of construction equipment. Because of soft soil, trees growing on the slopes may fall easier over the lines during heavy wind.

A possible rise in the ground water level has an influence on the underground cabling, as the cables may not resist the stress caused by water. As a result of higher ground water level, the conductivity of the soil increases together with the risk of corrosion of the guy structures.

Increased precipitation in winter together with the temperature rise provide favourable conditions for heavy crown snow load; branches or entire trees bend under the heavy snow load on the distribution lines causing a sustained fault.

As a consequence of heavy rains, floods are possible in cities, as the storm drainage system does not manage to drain water off the streets. Consequently, water may get into the basements and damage the transformers there. Floods in towns may also damage cable networks and distribution cabinets.

A change in temperature increases resistance (ohmic) losses. Changes in ohmic losses have an impact on the load losses of conductors and transformers. The need for cooling increases in transformers, thereby reducing their load capacity in hot summer weather, although more cooling energy would be required particularly in hot weather. The peak loads of many consumer groups increase during hot weather.

As a positive consequence of climate temperature rise, faults caused by very low temperatures in frosty weather will diminish or disappear altogether.

The negative air temperature sum will decrease and the ground frost period will shorten in the whole country. As a result, the construction and maintenance of electricity distribution networks will be more difficult on the soft ground, and trees will fall more easily on the lines.

4.5 Business environment of electricity distribution

Change in the business environment has been analysed in numerous publications (Partanen et al. 2005, Viljainen 2005).

The operational environment of electricity distribution companies has changed markedly after the opening-up of electricity markets. The development can be expected to speed up, and various new business models based for instance on services will more strongly reshape the operations in electricity distribution companies. In the future, an increased proportion of the companies' turnover will come from the contribution brought by the value network of several companies.

For instance the operations models of the Energy Market Authority as a regulator, the development of information technology, emphasis on customer service and the availability of human resources will pose new challenges for the operational environment of electricity distribution companies. The business objectives and regulatory models together with the opportunities provided by the modern technology will constitute an operational environment that calls for new operations models in the industry.

Factors strongly impacting the future distribution network business are regulation, tightening customer demands, business owner policy, technological development, ageing networks, climate change, and the general development in society for instance with respect to the location of population and utilisation of electricity.

The regulator aims at guiding the distribution network companies to intensify their operations and to lower their prices but also to guarantee the quality of electricity supplied to the customers. On the other hand, the targets of the business owners have become more business-oriented than they used to be.

The development of information technology provides numerous new operational opportunities. In the electricity distribution technology itself, no major development steps can be expected in the near future. However, by utilising the existing and coming technology, the present network concepts can be developed considerably further. The most significant technical factors guiding the development of distribution networks will be the reduction in undergrounding costs with respect to material and labour costs, the entering of new, lower-cost 110 kV line structures and 110/20 kV primary substations on the market, and the utilisation of the 1 kV low-voltage system. In the long term, exploiting power electronics in low-voltage DC distribution and an increase in distributed generation may be significant development factors.

Together with the climate change, the modern society's growing dependence on uninterrupted power supply will greatly influence the development of distribution networks and organisations. The climate change will increase the probability of the occurrence of weather conditions that may cause a major blackout (system breakdown).

Geographically, the population has gravitated towards population centres, that is, community, regional, and national centres. With respect to holiday homes, the trend has been the opposite. As a result of the concentration trend, a significant part of the distribution networks are located in areas where the increase in the use of electricity is only slight or even negative. Considering the development of distribution networks, this leads to a new situation; networks are developed to a minor degree for electrotechnical reasons only. Thus, the key factors guiding the development are reliability issues, the mechanical condition of networks and efficiency ideology.

Regulation, including an economic regulatory model and various detailed boundary conditions, is an instrument by which society and the prevailing policy can influence the operation principles of the distribution of electrical energy, which is among the fundamental infrastructures in the modern society.

The development of the regulatory model creates a key risk factor in planning the operations of an electricity distribution company, although for instance transition to the supervision of turnover will reduce the incentives of the present regulatory model that encourage to extensive network investments; this in turn has a direct impact on the reliability level of the network.

Irrespective of the future trends in regulation, certain basic questions remain to be answered. One of these is the question of whether it is at all possible to acceptably define the public services expected of the electricity distribution business. A key issue in this definition process is the acceptable level of the quality of supply. Another issue is the development of transmission prices, yet an unequivocal answer can hardly be found to this problem. The requirement for cutting the tariffs cannot always be the only basis for discussion, if the target is to develop the quality of supply and services.

Another basic question is related to the quality assurance of public services – shall we rely on economic regulation as a steering instrument, direct compensations paid to customers, or conditional fines imposed on network operators. The determination of an acceptable level of quality combined with pricing control may diminish the need for regulatory intervention in the reasonableness of individual cost components, such as operational costs, investments, or return on capital.

Hence, the supervision of electricity distribution business will probably develop to cover all the operations of a distribution company; it may include for instance the steering instruments related to the electricity quality and network investments, yet it has to be flexible enough and allow various business strategies, aiming either at maximising the return by actions controlled by the private owner itself, or reaching a “zero result” according to the targets of the public owner.

A possible scenario is a strict reliability requirement imposed by the authority, as is the case in Sweden; this may lead to a strong investment boom and rising transmission tariffs.

An alternative change in the business environment is related to the total differentiation of the monopoly activity from other business operations; an extreme example of this would be the nationalisation of the electricity distribution business.

5. Technology scenarios and solutions

5.1 Some technical solutions to the network development

The time span of electricity distribution network planning is long, typically several decades. As an output of network planning, on one hand, we obtain visions about the alternative operations to be implemented in the long term, but on the other hand, also concrete, detailed plans that can be immediately brought into practice. The needs for the network development are diverse; similarly, the range of implementation alternatives is wide. Below, we list some of the key methods for network development.

- Light (low-cost) 110/20 kV primary substations
- Light (low-cost) 110 kV lines
- Underground cabling (low- and medium-voltage networks)
- Plastic-covered overhead lines (PAS conductors)
- Building the line along the roadside
- 1000 V low-voltage electricity distribution
- Distributed protection (pole-mounted switchgear)
- Remote-controlled disconnectors
- Backup connections
- Control room automation
- Earth-fault current compensation (arc extinction)
- Backup power, microgrids
- Co-operation between national grid companies, service providers, and authorities

With these methods, it is possible to reduce the statistical average fault rates and durations. Protection against large climate disturbances can mainly be provided by underground cabling of the medium- and low-voltage network. Table 5.1 presents the effects of various methods on the fault rates and durations.

Table 5.1. Impacts of various methods on the fault rates and durations (↗↗ situation significantly improved, ↗ slightly improved, - insignificant or no impact).

	Number of sustained faults		Duration of sustained faults	Work interruptions	Number of reclosings
	Absolute	number/ customer			
Light distribution substations	-	↗↗	↗	-	↗↗
Light 110 kV line	-	↗↗	↗	↗	↗
Cabling (MV and LV networks)	↗↗	↗↗	-	-	↗↗
Plastic-covered overhead lines (PAS conductors)	↗	↗	-	-	↗
Building along the roadsides	↗	↗	↗	-	↗
1000 V distribution	↗	↗↗	-	-	↗↗
Pole-mounted switchgear	-	↗↗	-	-	↗↗
Remote-controlled disconnectors	-	-	↗↗	-	-
Backup supply connections	-	-	↗↗	↗↗	-
Control room automation	(↗)	(↗)	↗↗	↗	-
Earth-fault current compensation	-	-	-	-	↗↗
Backup power	-	-	↗	↗↗	-
Co-operation (authorities, national grid companies, service providers)	↗	↗	↗	-	-

5.1.1 Light 110/20 kV primary substations

The reliability of electricity supply can be improved quickly and efficiently by splitting up the present supply sections into smaller units. The most efficient way is to increase the number of primary substations. So far, a new primary substation has been an expensive solution, and the investment has been made only on the basis of strong growth in loads, and consequently, due to insufficient supply capacity. The electricity distribution company Suur-Savon Sähkö Oy has promoted the product development of primary substations together with a primary substation manufacturer. Together, the companies have managed to cut the price of primary substations into a half from the traditional model, the construction costs of the light primary substations being now about 500 k€. The notably reduced investment price allows the construction of new substations in the areas where the reliability of distribution networks has traditionally been low, yet due to the low load levels, there has been no justification for new primary substation investments.

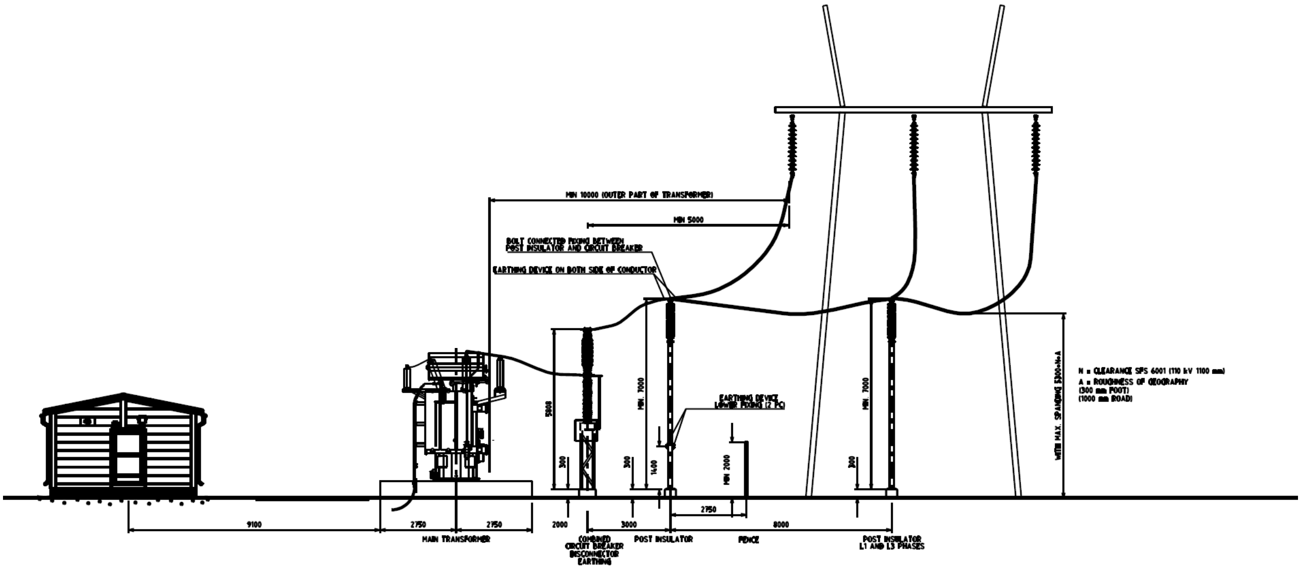

Figure 5.1. New light 110/20 kV primary substation.

In an underground cable network, when evaluating the need for a new primary substation, also factors other than reliability have to be considered. In practice, such are for instance a need to increase the transmission capacity and to add interconnections to the system.

5.1.2 Light 110 kV line

An essential component included in a new primary substation solution is the light 110 kV line developed in co-operation with the distribution company and the service provider. The solution is based on the limited supply capacity of a single, relatively small-size primary substation. When the power capacity of a primary substation is small, no large transmission capacity is required to supply it, and hence, light conductors with a small cross-sectional area can be employed. Consequently, also lighter pole structures can now be used. The short-circuit power of light primary substations can also be limited by the light lines supplying the substation. The thermal withstand capacity of 110 kV light lines is lower due to the smaller cross section, and the lines are protected with overcurrent and short-circuit protections at the supplying end. This protection acts simultaneously also as the protection of the high-voltage side of the light primary substation.

The construction costs of a light 110 kV line are about 60 k€/km. The investment costs are thus about 40 % lower than those of a conventional 110 kV solution and about two to three times higher than the costs of a 20 kV overhead line. The new construction will probably be taken into use for the first time in year 2008. Figure 5.2 illustrates the comparison of a 20 kV overhead line, a 110 kV light line, and a traditional 110 kV line.

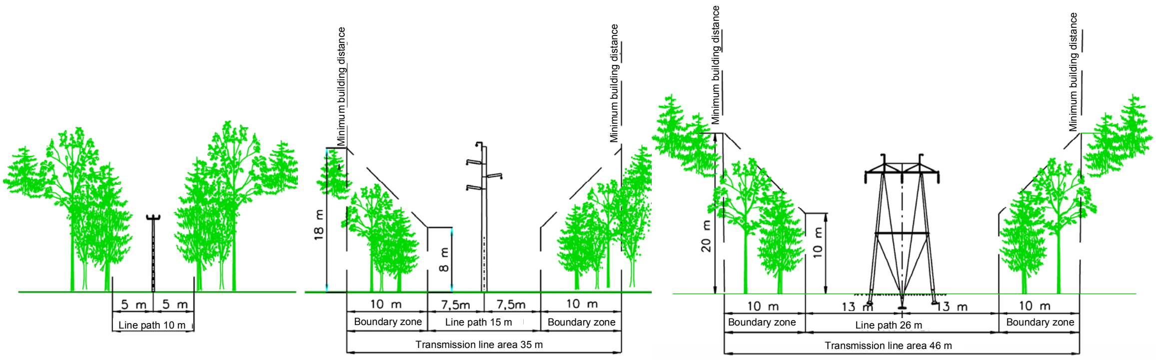

Figure 5.2. Line structure: a) typical 20 kV overhead line; b) new light 110 kV line (ELTEL, SlimLine); c) conventional 110 kV line.

5.1.3 Underground cabling

As stated previously, compared to overhead lines, reliability can usually be improved by applying underground cabling. The fault rate of underground cables is appr. 20–50 % of the fault rate of overhead lines. The location and repair of faults instead is more difficult in the underground cable network. When selecting the underground cable for the medium-voltage network, in addition to higher costs, also the increased earth fault currents and the backup connections required due to long repair times of underground cables have to be taken into account. The adaptability of the underground cable network is also lower and more expensive than in the case of an overhead line. The new branch lines at medium voltage require specific switchgear, a RMU (ring main unit) or branching from distribution substation. For branching in the low-voltage network, a distribution cabinet are required.

Figure 5.3 illustrates the feasibility study for medium-voltage cabling as a function of fault rate in a rural area compared to a conventional overhead line. The calculations are based on the new 2006 CENS (outage cost) values and on the old values from the 1990s. For plotting the curves, a typical fault rate, 5 faults/100 km,a has been employed as the fault rate of overhead lines. Further advantage is achieved by cabling also through the absence of reclosings. The idea is that a medium-voltage underground cable is installed by excavating in rural areas, and the cable includes the required joints and terminations. In that case, the price of an AHXAMK 70 underground cable is about 44 000 €/km. This value is compared in calculations with a Raven overhead line structure, the installation costs of which are about 19 600 €/km (EMA-2006).

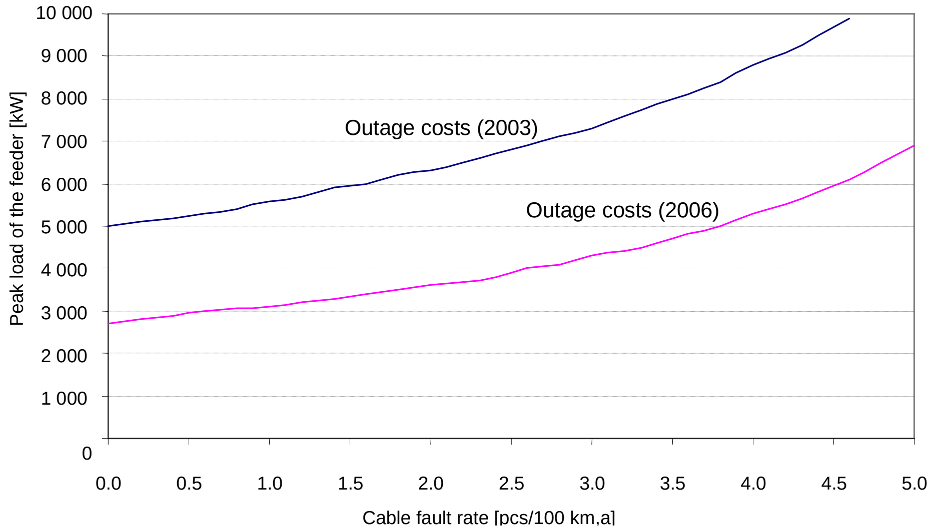

Figure 5.3. Feasibility studies for a medium voltage cable with new and old outage costs on a certain feeder. Customer distribution: residential 43 %, agriculture 7 %, industry 17 %, public 12 %, service 21 %. Supply restoration time for overhead lines is 0.5 h and for underground cables 1 h.

The figure shows that outage costs have a significant impact on the range of economic feasibility of undergrounding. As the outage costs applied in the regulation and the future changes are yet not known, the decision-making related to these issues always involves a significant financial risk caused by the regulation.

The good reliability of cables is emphasised during large climatic disturbances. Changing over to underground cables is almost the only way to surely prevent extensive and long-lasting interruptions typically caused by severe storms in overhead networks. However, the high price of underground cabling limits the larger-scale utilisation of cables in network construction. The construction of a medium-voltage cable is particularly expensive. Nowadays, underground cables are chiefly installed by applying excavation technology, and the cable itself is notably more expensive than for instance a low-voltage cable. Therefore, preconditions for a wider utilisation of underground cabling are the development and application of lower-cost cabling methods. Cost savings can be achieved by developing the cable structures, by using low-voltage cables instead of medium-voltage cables (utilisation of 1 kV and DC technology) and by developing the cable ploughing methods.

5.1.4 *Ploughing of low-voltage cables*

Cable ploughing as a low-voltage cable installation method is becoming increasingly common especially in rural areas. Nowadays, when the circumstances allow it, nearly all low-voltage underground cables are installed by ploughing. This way, the installation costs can be kept reasonable; consequently, low-voltage cabling is a more inexpensive solution than the conventional AMKA aerial bundled cable structures. The overall cable ploughing costs are in average 50 % lower than the excavation costs of a cable trench alone in rural areas. The soil somewhat restricts the potential targets for cable ploughing; nevertheless, ploughing is possible everywhere except in a very stony or rocky soil. A survey in the area of Suur-Savon Sähkö Oy (SSS) showed that ploughing is an applicable method in 80 % of the total low-voltage network. Usually, preferable areas for cable ploughing can be found by the roadsides and road beds. Ploughing speed depends on the scope of the target; however, it can be several kilometres a day. Figure 5.4 illustrates low-voltage cable ploughing into a gravel road leading to a summer cottage.

Figure 5.4. Ploughing of a low-voltage underground cable.

5.1.5 Covered conductor overhead line (PAS conductor)

In medium-voltage networks, plastic-covered overhead lines (PAS conductors) are employed to some extent. Their insulation structure is simple and inexpensive. The amount of insulator material on the conductor surface is sufficient to prevent an electric breakdown if conductors come momentarily into touch, and correspondingly, a line may support a fallen tree even for several days. With a proper insulation structure, the phase conductor spacing of the overhead line can be reduced, which enables a narrower line path particularly in the case of double and triple lines. The reliability of this conductor structure is also better than that of a bare overhead line, since tree limbs or birds on the line do not cause an interruption through high-speed or delayed autoreclosing. The number of interruptions caused by branches or trees leaning on the line cannot however be much reduced by PAS conductors. With PAS conductors, branches and trees do not cause an immediate interruption, but in the course of time, damaging of the insulation causes a sustained interruption. Trees falling or bending on the line may also cause a safety risk: because of the insulation, a tree bent on a line will in the course of time cause a high-impedance earth fault that is not easily detected by the earth-fault protection. Simultaneously, the step and touch voltages in the surroundings of the fault may rise to a hazardous level.

The investment costs of PAS conductors are 30 % higher than those of corresponding bare overhead lines. They are an economically feasible solution for double or triple lines starting from primary substations, but also in demanding reliability conditions, for instance in areas with a risk of heavy snow loads.

PAS conductors have typically been installed to the roadsides. One of the reasons for this has been that the lines can be easily accessed for checking. A check-up should always be performed after a storm to ensure that there are no trees on the lines remaining undetected by the protection. Typically, because of its insulation, a PAS conductor is difficult to repair after a fault. Furthermore, it is difficult to detect a damage caused by a tree on the insulation material, and in general, damages in the insulator may also later cause unexpected fault situations. Figure 5.5 shows a covered PAS overhead line built along the roadside.

Figure 5.5. Covered conductor PAS overhead line along the roadside.

5.1.6 Building the lines along roadsides

In rural areas, most of the lines and line paths are located in forests. The solution dates back to several decades, when the target was to minimise the material costs in network construction investments. This usually meant the construction of lines straight through forests to minimise the line lengths. In the peak years of electrification of rural areas in the 1950s and 1960s, bringing lines to forests was usually not a problem with respect to land-use contracts. In some areas, there was almost a competition between the farmers for getting the power line on the property, since this usually guaranteed also a service connection for the landowner. The reliability of supply, however, was not among the central issues those days. At that time, the quality of electricity supply was typically understood to depend only on the voltage level. The quality of supply did not depend on the interruption rate or the number of other disturbances but on a small voltage drop or high enough voltage rigidity. In addition to cost savings, building the lines in forests has been justified by invisibility of the lines in the vicinity of built-up areas. Unlike lines along the roadsides or on the fields, the lines in the forests are quite invisible. Furthermore, placing the lines along the roadsides is still somewhat problematic due to the opposition of road providers against electricity distribution lines along roadsides; a line built too close to the road may be an obstacle to the road maintenance.

Now, several decades later, the reliability of supply has become a focal boundary condition in the network planning. Therefore, the target is to construct new lines along the roadsides whenever possible to improve reliability and facilitate the maintenance. There is practical evidence that transferring the line to the roadside cuts the number of faults into half in these line sections. Figure 5.6 illustrates a typical situation in a 20 kV medium-voltage network. The line path goes straight through the forest, although there would also be a more sheltered route available along the roadside.

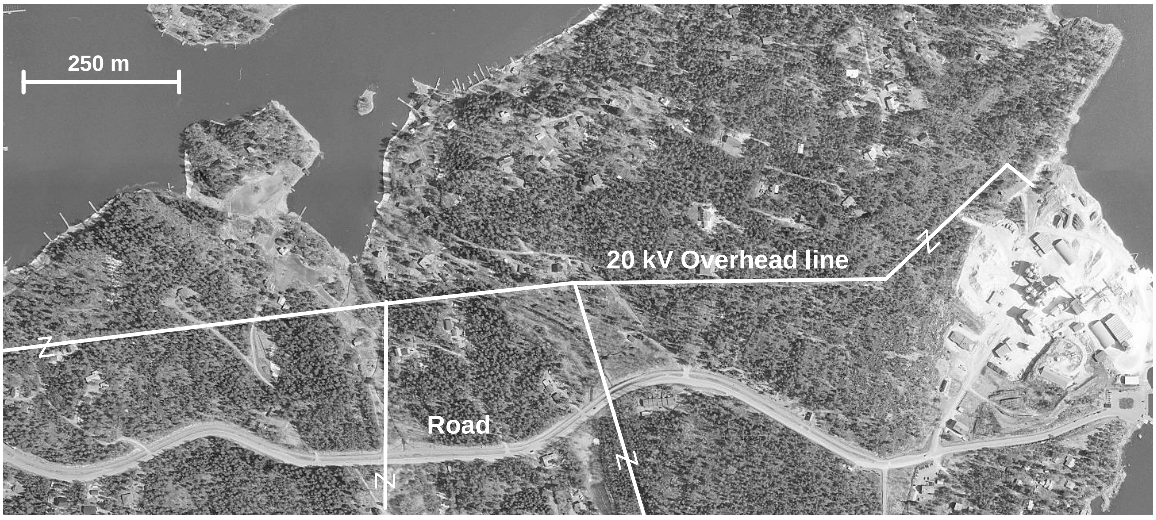

Figure 5.6. Typical 20 kV medium-voltage line route in rural area. The line path is located in forests although a more sheltered route would be available close by the roadside.

Already in the early days of electrification, habitation and thereby the loads have been located in the vicinity of the other infrastructure, that is, near the roads. In that case, it is often necessary to build branch lines from the lines in the forests to these loads along the roadsides. In the course of time, the placement of loads along the roadsides has become increasingly common. Nowadays, making land-use contracts for building new lines in the forests has become more difficult. Landowners do not want a power line on their property, nor do they allow cutting trees for the construction of distribution lines. Electricity distribution is taken for granted, yet it should be invisible and the network structures may not cause any changes in the environment. When the line is moved to the roadside, it becomes visible, yet it is often considered a smaller disadvantage for instance compared with falling trees to build a new line. Furthermore, the distribution line along the roadside is usually closer to the actual load nodes. When we also take into account the present compensations paid for the land use, building the line along the roadside does not lead to a more expensive solution than building in the forests. Neither do the line lengths change considerably. The solution is also environmentally friendly, since it utilises routes that have already been cleared for the road.

In the roadside, the road-side part of the line path is already cleared and ready for the line construction. When moving the power line to the roadside, the line is located on that side of the road, where the wind usually blows.

5.1.7 1000 V low-voltage electricity distribution

The utilisation of 1000 V low-voltage distribution can be considered to be among the most promising new technologies. Since 90 % of the interruptions experienced by customers are caused by faults in the medium-voltage network, the reliability of power supply can be improved remarkably by reducing the size of supply sections, which at the same time also define a fault's range of influence. With the 1000 V technology, it is possible to cost-efficiently change low-power and fault-prone medium-voltage branches to operate at 1000 V low voltage. The fault rate and their range of influence will decrease considerably, as each branch implemented with 1000 V technology constitutes a protection zone of its own and thus, in the occurrence of a fault, does not affect customers in other supply sections of the same medium-voltage network. Furthermore, at 1000 V voltage, it is possible to employ the existing AMKA aerial bundled cable structures, which are far more reliable than the bare overhead line structures. While with the 400 V low-voltage distribution, the maximum distance between the customer and the distribution substation remains below one kilometre due to the voltage drop, with the 1000 V technology, it is possible to supply customers at a distance of one to five kilometres. Depending on the area observed, 10 to 30 % of the present medium-voltage network length could be replaced with the 1000 V technology. A rough estimate is that this would decrease the number of interruptions experienced by customers by up to one third. Generally defined, feasible techno-economical targets for 1000 V lines as a replacement for 20 kV lines appear in the range in which the transmission power of the branch lines lies below 60 kW and the transmission distances are from one to five kilometres; in the underground cable network, the transmission power of branch lines is less than 100 kW and the distances lie between one and five kilometres (Partanen 2005b; Lohjala 2005).

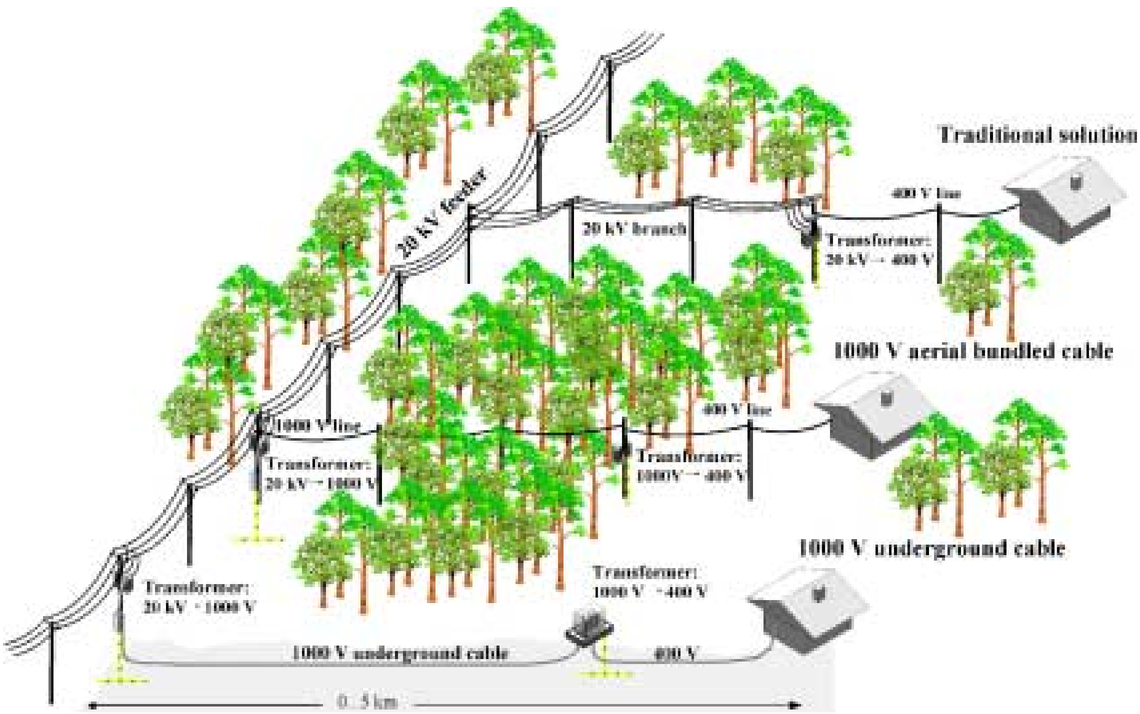

Figure 5.7. With the 1000 V technology it is possible to replace low-power 20 kV medium-voltage branches cost-efficiently.

The 20/1/0.4 kV three voltage level distribution system is already as such applicable to large-scale use. In new construction targets, the most significant potential of the 1000 V system lies in targets, where the 1000 V lines can remove the need to construct new medium-voltage lines. The 1000 V system is a profitable solution also when new customers have to be connected to the network, in which case the electrification would require the division of the transforming district or constructing of very strong 400 V lines. An economical solution can usually be found by using 20/1/0.4 kV three-winding transformers. The 1000 V system enables the construction of larger low-voltage transforming districts than it was possible in the conventional system. In a transforming district of this kind, the main line is a 1000 V line with several 1/0.4 kV transformers connected to it. In practice, the use of 1000 V structures in the renovation of the network always requires at least partial renewal of the existing network topology. The 1000 V system decreases the traditional division of transforming districts and hence the number of HV/LV distribution substations. However, the total number of distribution substations increases or remains at least at the same level due to the 1/0.4 kV distribution substations (Lohjala 2005; Partanen 2005b). When properly designed, a 400 V network becomes typically 0–30 % shorter. The total network length, however, remains approximately unchanged.

In renovation targets, the 1000 V system is worth considering as a possible alternative for the conventional system. A comprehensive renewal of a medium-voltage line, even if the routings remain unchanged, corresponds to a new construction target with respect to the use potential of the 1000 V system. If the renovation (reinforcement) concerns only the poles of the medium-voltage line, the potential of use of the 1000 V system is more limited than that of new construction targets. Often a fault-prone medium-voltage branch can be separated as a protection zone of its own by using it as such in 1000 V operation. The investment costs of the commissioning of the 1000 V system are often lower than those of medium-voltage pole-mounted switchgear. However, the profitability of a solution of this kind is chiefly based on lower interruption costs (Partanen 2005b).

The pursuit of better reliability may require undergrounding of the medium-voltage network in rural areas. However, the power transmitted in many medium-voltage feeders in rural areas is often too low for economically profitable underground cabling. A possible alternative is using 1000 V low-voltage underground cables instead of medium-voltage cables. The profitability of 1000 V underground cables is based on the lower investment costs compared with medium-voltage cables. The investment costs of the 1000 V underground cable system in rural areas are more than 50 % lower than the costs of medium-voltage cables.

5.1.8 Pole-mounted switchgear

On the medium-voltage feeder, remote-controlled pole-mounted reclosers with protection relays can be used; this reduces the number and duration of faults seen by the customer. The achieved benefit depends on the length of the network downstream from the recloser (the number of faults) and the number and type of customers upstream from the recloser. The customers upstream from the recloser do not experience an outage during faults that occur downstream from the recloser. Figure 5.8 illustrates a possible location of a pole-mounted recloser. The price of the pole-mounted recloser and the required protection relays is around 28,000 €.

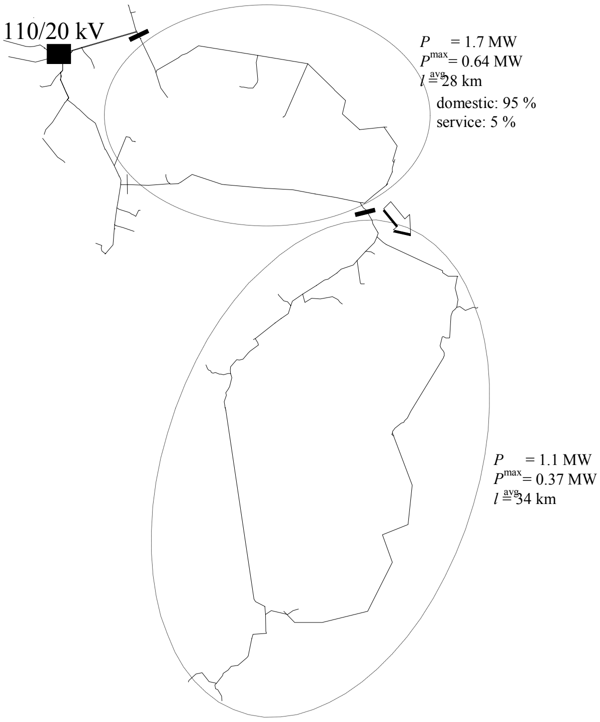

Figure 5.8. Possible placement of a pole-mounted recloser on a medium-voltage feeder.

	Max Design Voltage, kV	Contunuous Current, A	BIL, kV	Interrupting Current, kA
OVR-3	15.5	630 / 800 / 1000	110 / 125	12 / 16
	27	631 / 800 / 1000	125	12 / 16
	38	632 / 800 / 1250	170	12 / 16

Figure 5.9. OVR-3 pole-mounted recloser (Hakola 2005).

Figure 5.10 illustrates the feasibility studies for a pole-mounted recloser on the example feeder.

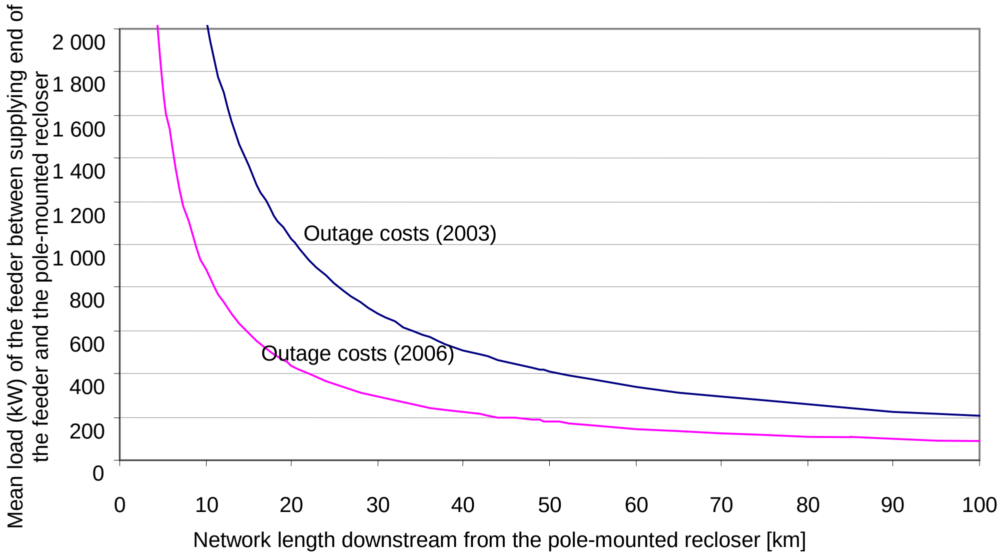

Figure 5.10. Feasibility studies for a pole-mounted recloser on a feeder according to the old and new outage cost values.

For instance the mean load between the supplying end of the feeder and the pole-mounted recloser is 640 kW and the network length behind the recloser is 34 km. In the case illustrated above, the investment would be economically profitable, if the outage costs are paralleled directly with the investment costs of the distribution company.

5.1.9 Remote-controlled disconnectors

With a remote-controlled disconnector, the duration of fault outage experienced by customers can be reduced; however, the number of outages cannot be influenced by disconnectors. The positive effect is achieved through the shortened switching time. The time required for the manual control of a disconnector is typically tens of minutes depending on the location of the disconnectors and the physical placement and level of readiness of the repair staff. With remote control, the system can be controlled in few minutes; in particular, the time required for the isolation of the fault point and switching of the backup connections can be considerably reduced. After isolating the fault point, the number of customers without power supply is usually reduced to a fraction of the initial state, in which all customers of the faulted medium-voltage feeder are without supply.

A remote-controlled disconnector substation as such does not directly increase the transmission capacity of the network. However, remote control can indirectly increase the transmission capacity of the network, as it enables rapid implementation of complicated backup supply arrangements in serious fault situations. This allows full utilisation of the network capacity, and thus reduces the investment needs.

A remote-controlled disconnector substation comprises a disconnector unit, a control handle, a motorised spring operating mechanism, control electronics, radio unit, and antenna. The remote control is usually placed at central branching points and at the boundaries of neighbouring feeders of the network. At a single disconnector substation, typically two to four disconnectors are included within the control. The price of a remote-controlled disconnector substation (two disconnectors) is around 16,000 €.

Figure 5.11. Remote-controlled disconnector substation.

5.1.10 Construction of backup connections

It is possible to influence the interruption durations by changes in the network topology. With respect to reliability, the interruption durations of problem targets can be reduced with a backup supply connection. A backup supply connection can refer for instance to a link arrangement, that is, an interconnection between two radial feeders, which is not in use under normal operating conditions. On the other hand, backup connections can be built to the network of a neighbouring distribution company; this way, the interruption durations can be reduced during major faults. The reliability of supply increases together with the increasing number of backup supply connections; however, constructing backup connections that are in principle useless under normal operating conditions is not always an economical solution everywhere in the network. Therefore, it is not economically profitable to construct backup supply connections, if the distance between the end points of the connection is very long. Also when planning backup supply connections, the limit for acceptable voltage drop should not be set too tight; otherwise, the backup structure becomes too expensive or even technically impossible to implement.

Building backup supply connections between different distribution companies is also a part of strategic preparation for severe fault situations. The construction of backup supply connections is usually analysed in connection with the replacement considerations of a faulted primary substation. In these cases, the number of customers without supply is usually so large that it is advisable to provide backup connections for at least a part of the network that is normally supplied by the faulted primary substation.

The efficient use of backup connections and advantages gained by them is directly linked with the efficient utilisation of network automation and distribution management functions. To reach the best results, the backup supply connections should be connected to the network by remote-controlled switchgear. The remote control of disconnectors enables fast switchings to isolate the faulted network section immediately after a fault has occurred, and the power supply can be restored in the section through backup connections. The duration of the interruption and the outage costs depend on the time required for switching on the backup supply.

5.1.11 Control room automation

The reliability and full-scale use of the transmission capacity can be improved in many ways by utilising the functions of the distribution management system. With the calculation functions in the distribution management system, it is possible also in difficult fault situations to quickly and accurately determine the opportunities to apply the backup supply connections to ensure that the requirements set for the network protection and voltage quality are still met. The calculations together with the application of remote-controlled disconnector substations enable the full utilisation of the network transmission capacity. This will cut the network investments in the long term.

With the fault location functions in the distribution management system, it is possible to speed up the location and isolation of short circuits occurring in distribution networks. An efficient fault location system requires a modern processor-based protection relay at least in the main supply at the primary substations; this protection relay can measure and store the fault current values and send the information to the distribution management system in the control room. The fault location can be developed further also by employing fault detectors that are read either locally or through remote connections. A fault detector starts when a fault current flows through it. If the operating information of the fault detector is transmitted by remote reading to the control room, the fault can be located fast also in the case of earth faults.

Many distribution companies have managed to considerably cut down their customers' outage costs caused by faults by adopting fault detectors and protection relays capable of measuring fault currents, control and distribution management systems, and remote-controlled disconnector substations.

5.1.12 Compensation of earth fault current

A single-phase earth fault causes at the point of fault an earthing voltage, the magnitude of which is determined by the fault current and the earthing resistance met by the fault current. A part of the earthing voltage may cause a hazardous touch voltage to humans or animals. In Finland, the specific conductivity of soil is usually so low that it is not easy to achieve low earthing resistances in the protective earthings at the distribution substations and disconnector substations, nor in the operational earthings of the low-voltage network; the earthing resistances are typically of the order of a few ohms. This is the main reason why the medium-voltage network is operated as isolated from ground in Finland. In an isolated system, the earth-fault current is low, and thus the earthing voltages remain moderate, and the requirements set by the electrical safety regulations can be met. However, also in circumstances, in which the earthing conditions are particularly difficult, for instance in ridge areas, it is difficult to reach the permissible values for earthing voltage. In these cases, instead of increasing the amount of copper used for earthings, a possible alternative may be to reduce the earth-fault current by employing a centralised or decentralised compensation of the earth-fault current.

In centralised compensation, a reactor is installed at the primary substation between the star point of the 20 kV network and earth. The inductance of the coil is dimensioned such that the inductive fault current flowing through it corresponds to the capacitive earth-fault current flowing through the line capacitances. Now the total earth-fault current causing earthing voltage becomes very low, as the capacitive and inductive currents cancel each other. In addition to arc extinction centralised in the primary substations, also the so-called decentralised compensation is applied in Finland. In the decentralised compensation, 5 or 10 A earthing transformers are used, located at different points on the 20 kV feeders (the inductance is located in the earthing transformer between the primary star point and earth). Also in this alternative, the target is to reduce the earth-fault current.

In addition to the reduced earthing voltages, a further advantage of the earth-fault current compensation (arc extinction) is a decrease in the autoreclosing functions caused by earth faults. In a compensated network, a part of the earth fault arcs extinguish itself without any autoreclosing function required to de-energise the network. With extinction, it is thus possible to reduce the number of autoreclosings in the network. Considering the basic solutions for earth fault compensation is among the key issues in the long-term distribution network planning. Due to the high earth capacitance of the underground cables, the compensation of earth fault current is in practice necessary in large medium-voltage cable networks.

5.1.13 Backup power

The electrotechnical development needs in the medium-voltage network are quite often due to the lacking transmission capacity during serious fault situations (such as a main transformer failure). In the electricity distribution network, there are always targets, the reliability of which cannot be improved with reasonable costs by changing the network structure. In situations of this kind, it is possible also to utilise equipment intendend for other than power transmission purposes; such as backup power generators and compensation capacitors. If the targets involve critical customers, such as large farms, industry, or public health services, the application of backup power can be a justified short-term solution. Critical customers are customers, the outage duration of which may not in any circumstances exceed one hour.

The distribution company can take advantage of backup power generators to increase the transmission capacity of the 20 kV network during severe failures. During serious fault situations, backup generators can be switched into operation either at the primary substation in the faulted area or on the 20 kV line. The power generated by the backup generator (100–1000 kW) does not have to be transferred through the 20 kV network; consequently, a larger power as a whole can be achieved in the area of the failure. However, it has to be borne in mind that also the additional capacity obtained by the backup power generator is usually low when compared with the total loads of the network; nevertheless, even a small addition to the power capacity may be a decisive factor enabling the postponement of a large and costly network investment into future.

Similarly as backup generators, battery backups could be used in serious fault situations. However, the procurement costs of battery technology are still so high that they are not a realistic option in electricity distribution networks (Partanen 2006).

As long as the distribution network includes overhead lines, the network is susceptible to the weather-induced faults. On the other hand, in the underground cable networks, the repair time may be rather long even if the fault rate were low. A customer’s time without supply can be cut in these cases by using backup power at the customer’s premises. Nowadays many farms in rural areas have acquired generator sets to secure power also during severe fault situations.

From the viewpoint of the distribution company, it is expensive to keep up the backup power facilities acquired for purposes other than maintenance use. Expensive equipment may lie unused for long periods of time, yet they have to be kept in working order. Instead, installing backup power generators for certain critical customers may be justified; this way, certain network investments that would otherwise be required can be reduced and postponed to a later date. However, if backup generators are installed, the question of cost allocation remains to be solved. If the investment costs are covered by the transmission tariffs of the whole clientele as usual, all the customers will have to pay for the service that benefits only a few of them. The simplest solution is thus that the customer procures the backup power equipment and takes care of its upkeep at customer’s own expense.

5.1.14 Microgrid systems

If we wish to take advantage of the improved reliability/power quality resulting from the growing distributed generation and developing energy storages, we have to utilise microgrid systems. A microgrid is a system that is, if required, capable of independent island operation; it is a part of low-voltage network including some local generation and consumption and also one or two energy storages. The concept originated chiefly in the U.S., where various new solutions have been searched to improve the reliability of electricity supply as an answer to the widespread problems and interruptions in the electricity supply during the past few years. In recent years, extensive projects have been launched also in the EU in order to investigate the applicability of the concept in

Europe. Generally speaking, microgrid systems are assumed to improve energy efficiency, to reduce total energy consumption and the environmental effects of energy generation, and finally, to improve reliability and the cost structure of the distribution network.

In distribution networks, the lowest voltage level is the 400 V low-voltage system (three-phase), the distribution transformer of which forms a natural connection point between the microgrid and the distribution network; it can be compared with a present consumer connection point. The low-voltage section that forms the microgrid or only a part of it can be switched either pre-planned or in the occurrence of fault to island operation, and then reconnected to and synchronised with the rest of the grid as the fault has been cleared. Figure 5.12 depicts a simple microgrid. Microgrids are also considered an important way to implement a non-discriminating distributed energy system by utilising small-scale generation units. At the same time, they are seen as an opportunity to flexibly connect small units to the grid (plug-and-play). A microgrid has an own, independent distribution/energy data management system for the local network that manages and controls the network in island operation, yet it may also act in cooperation with a larger distribution/energy data management system of the total distribution network.

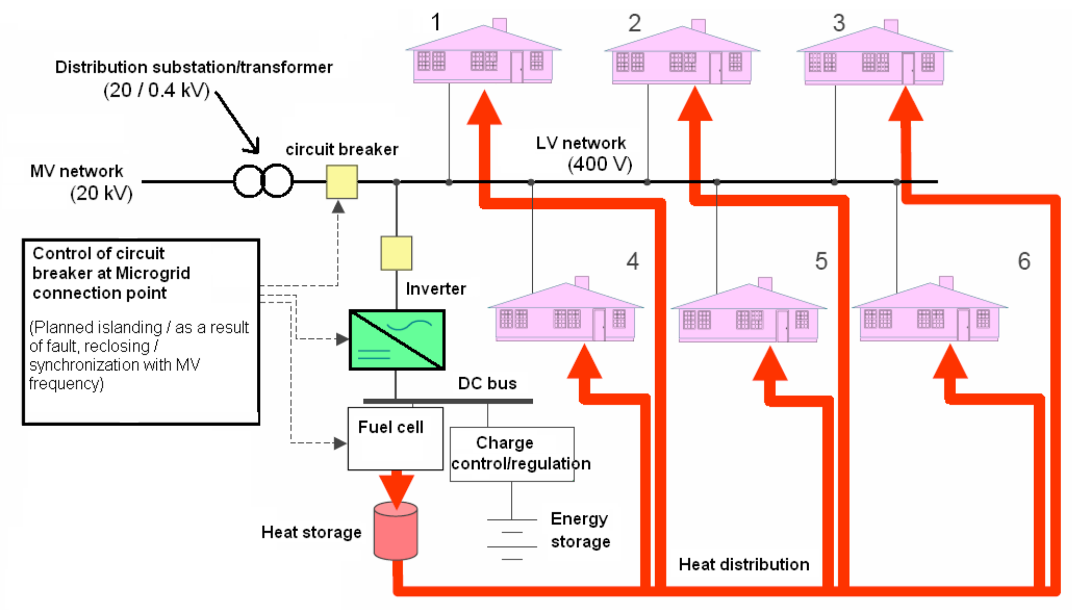

Figure 5.12. Example of a simple microgrid. (Goodman, F., Open Communication for Distributed Energy Resources (DER) in Advanced Distribution. Presentation for FY04 Peer Review, DOE Electric Distribution Transformation Program, October 28-30, 2003.)

If a microgrid is built from an existing network structure that still has some useful (technical and economical) lifetime left, an AC microgrid is probably the most inexpensive and advisable solution. When constructing a new low-voltage network instead, a DC network should be considered, although it would initially not be capable of island operation as a microgrid due to the lacking/insufficient distributed generation/energy storages. In the future however, there will be flexible solutions to connect distributed generation and energy storages to the network and thereby also to implement island operation. Considering these two network solutions (AC/DC), we have to bear in mind that the solutions both require completely different protection and management systems for power balance. In DC microgrids for instance, it is possible to get rid of systems required for the frequency control and synchronised reclosing of the island system, yet the implementation of the protection system may prove a challenging task. Connecting rotating electrical machines and AC consumers to a DC network always requires a frequency converter, but on the other hand, generator/motor drives equipped with frequency converters in an AC network do not need a line converter in a DC network.

5.1.15 Co-operation with other organisations

Trees bending or falling on the overhead lines cause aconsiderable portion of the faults in a distribution system. The fault rates can be significantly reduced by regular clearing of the line path, by cutting off branches extending to the line path, and by removing risk trees adjacent to the line path. In particular, young birches and other deciduous trees constitute a risk, as they bend under snow load over the overhead lines. Clearing performed by a helicopter has proven to be the most efficient method in cutting the tree limbs growing over the line path; in the method, a long chain saw suspended under the helicopter clears the edges of the line path. The method ensures that trees under snow load will bend or fall away from the line path and the power line.

The right of use of the line area is based on an agreement between the distribution companies and landowners. The distribution company pays the landowner a compensation for the land use. The problem caused by trees outside the line path are is not removed by clearing the line paths, but also tall and slim deciduous trees in the vicinity of the line but outside the line path should be removed.

A distribution company has a right and obligation to remove a tree bending on the line area or towards an overhead line, if it constitutes a hazard to humans or a risk of supply interruption. However, the agreements between distribution companies and landowners do not necessarily guarantee a right to preventive cutting of risk trees outside the line area. An advisable solution would be that forest owners could solve the problem in conjunction with network operators as a part of larger silvicultural measures in the area. This way, the electrical safety and reliability of supply could be improved, and no significant harm would be caused to the forest growth and development.

Co-operation with local forestry societies has proven to be efficient especially in reducing faults caused by seed tree areas; when no seed trees are left in the vicinity of power lines, several outages caused by a tree falling on the line can be prevented. Also co-operation with forest harvesting enterprises is advisable; most of the mechanised logging operations are performed by forest harvesters, and the risk of a tree falling on the line is particularly high when operating in darkness.

Mechanical excavations account for the majority of cable damages in the underground cable networks in population centres. The number of incidents damaging cables during earthworks can be reduced by instructing the excavation companies not to proceed with the earthworks before contacting and consulting the distribution company. This way, the number of cable damages has been reduced.

As described above, some of the long-term development measures influencing on the network are not limited only to the development of the lines and cables or the organisation of the distribution company, but the co-operation with several other interest groups is also a focal part of the strategic development of network operations.

5.1.16 Power electronics in electricity distribution

Nearly all of the technologies and methods described earlier in this report are already available everywhere. The next major step in the development of electricity distribution would be the adoption of power electronics in the development tool kit. The Low Voltage Directive (LVD) 73/23/EEC defines the maximum value of low voltage to be 1000 V AC and 1500 V DC. So far, low voltage has been applied only to the AC supply, while the DC supply has received less attention. The improvement in the component quality and characteristics together with lower prices make power electronics a viable solution in various new applications.

An example of the structure of a distribution network with power electronics is illustrated in Figure 5.13. The 20 kV branch line, 20/0.4 kV distribution substations and 0.4 kV low-voltage lines of the conventional solution are replaced with a 20/LV transformer, an AC/DC rectifier, DC cable and a DC/AC inverter at each end user.

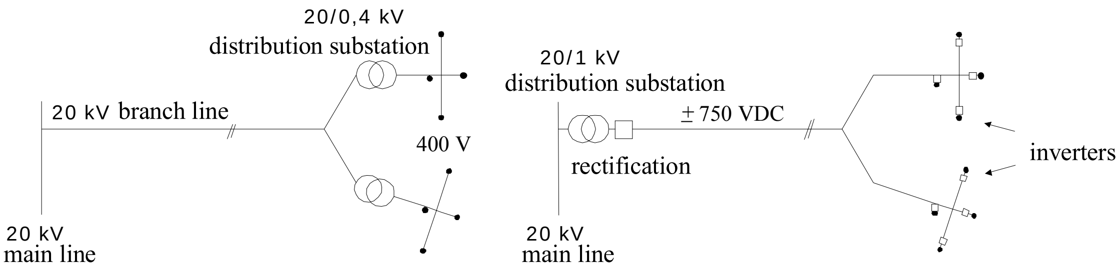

Figure 5.13. Example network. On the left, the electrification is implemented with a conventional 20/0.4 kV technology; on the right, with a ± 750 V DC system.

Benefits brought by power electronics

DC transmission has several advantages compared with AC transmission; with DC, the supply voltage can be higher due to the definitions of the AC and DC voltage ratings in the Low Voltage Directive. With DC, it is possible to transmit a higher power than with AC, and consequently, some branch lines can be replaced with a DC connection. If the protection of the DC connection is implemented with line protection devices (circuit breakers), each DC connection constitutes a protection zone of its own, which improves the reliability of the distribution system. If a medium-voltage branch is replaced with a DC connection (similarly as a 1 kV system), lower total costs can be achieved.

The end-users' problems caused by voltage drops will decrease, if the 0.4 kV voltage level is produced directly with an inverter; now, larger voltage drops can be allowed on the DC transmission lines than what is typically allowed in the AC networks, since the inverter can produce the AC for the customer also from a DC voltage that is notably below the rated DC voltage. A further advantage of the DC system is also the connectivity of distributed generation to the network.

Challenges faced by power electronics

Application of DC voltage in electricity distribution requires rectifiers and inverters at both ends of the DC voltage level. This increases the number of components in the distribution network, although the inverters replace the low-voltage transformers altogether. An increase in the number of components may lead to a more fault-prone distribution network and may increase the number of interruptions experienced by customers.

As a result of the operation of the converters, there occur harmonics in the network, which are seen both by the consumer and in the supplying network. Harmonics may degrade the power quality experienced by the customer. To prevent disturbances, it is possible to utilise various filtering solutions provided by power electronics.

The lifetime of power-electronic components is shorter than the lifetime of the conventional network components. In particular, the lifetime of the power-electronic devices depends on the lifetime of blowers and capacitors included in these devices.

Price development of power-electronic devices

The price development of industrial products in the past few decades is presented in Figure 5.14. The figure shows a steady decline in prices for electronic goods during the past decades; the prices have more than halved between 1995 and 2005. At the same time, the price development of the products of mechanical engineering and metals industries has been opposite to the price development of power electronics goods, which promotes the opportunities of the DC distribution system.

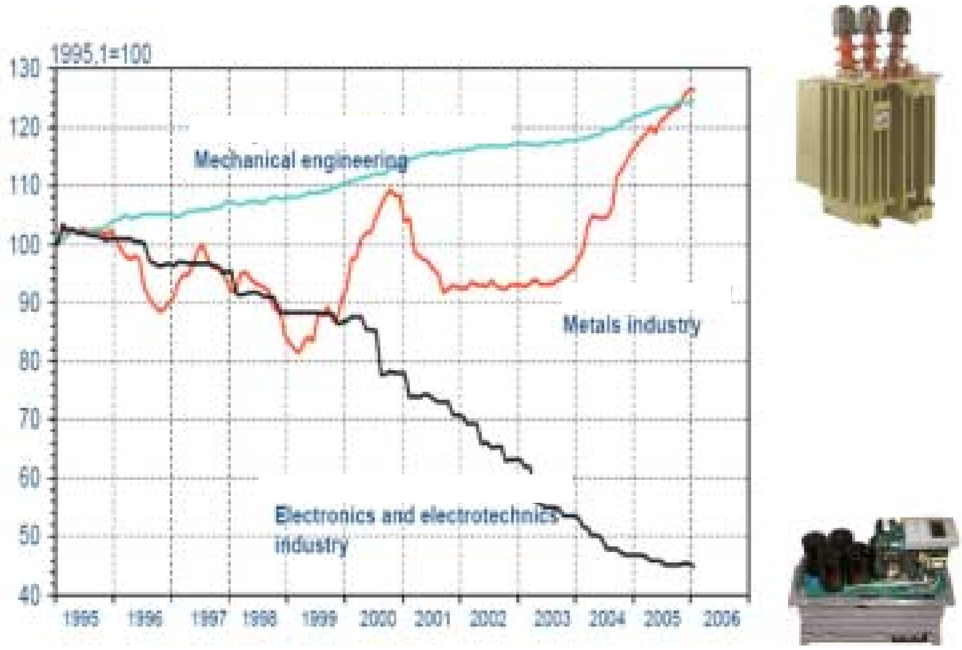

Figure 5.14. Development of producer prices in technology industries between 1995 and 2006 (mechanical engineering, metals industries, electronics and electrotechnical industries) (Statistics Finland / Technology Industries of Finland).

Technical implementation

There are two alternative approaches to the implementation of a DC system; depending on the implementation method, a DC system is either a uni- or bipolar system. The differences of uni- and bipolar DC system lie in the number of voltages used, the number of converters, and the technical characteristics of the systems.

As the maximum low voltages, the Low Voltage Directive defines 1000 VAC and 1500 VDC. With DC, the peak value for the voltage is the same as the rated value, and thus, at low voltage, the maximum potential difference between the input and output poles may be 1500 VDC. Now, the supply voltage in a unipolar DC system can be 1500 VDC at maximum, and in a bipolar system ± 750 VDC, if the three-phase low-voltage cable is brought up to the end-user connection point. By branching the transmission line of the bipolar system into two unipolar lines, the maximum voltage in the main line section can be ± 1500 VDC, if only one of the used voltage levels (+/-) is brought to the end-user connection point.

The power transmission capacity of DC and AC systems is illustrated in Figure 5.15.

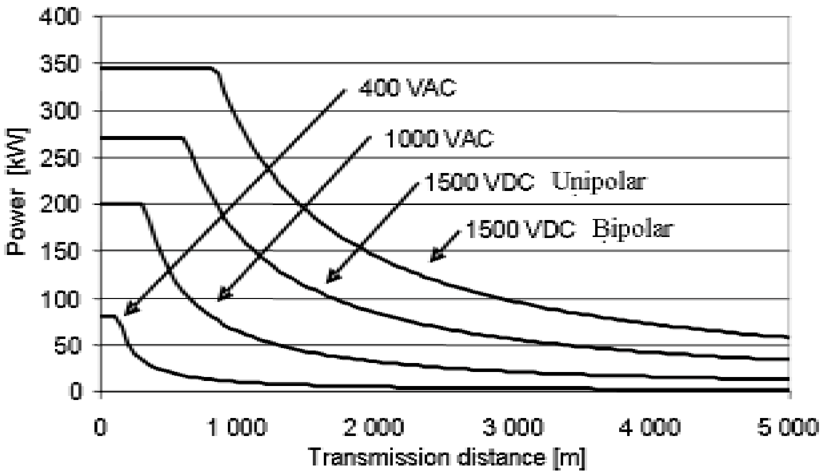

Figure 5.15. Transmission capacities of electricity distribution systems in different technical solutions. The conductor in all cases is a 3 x 35 + 70 mm^2 one and the maximum permissible voltage drop is 6 %.

The figure shows that for instance with 400 VAC, a power of 50 kW can be transmitted to the distance of 200 m, while with an unipolar system, the same power can be transmitted to the distance of 3300 m and with a bipolar system to 5700 m. The transmission distance coefficients become thus 16.5 with the unipolar system and 29.5 with the bipolar system.

The power transmission capability between the systems can be inversely utilised by employing smaller cross-sections for a DC network than for an AC network in the low-voltage network. With smaller cross-sections, lower conductor investment costs can be achieved. Correspondingly, the high power transmission capacity of the DC system can be utilised by replacing low-power medium-voltage branch lines with DC cables.

The utilisation of a DC system may bring notable investment cost reductions; even more than 50 % savings can be reached. The costs of power electronics are added on these costs. According to preliminary analyses, these additional costs are lower than the benefits achieved.

In the Finnish electricity distribution system, the DC service may have a large use potential. Thanks to the transmission potential of the DC system, nearly all the branch lines could be replaced in the medium-voltage network with a DC system. Only the main line of the feeder would remain in the medium-voltage use. Figure 5.16 depicts the use potential of the DC system in a medium-voltage network.

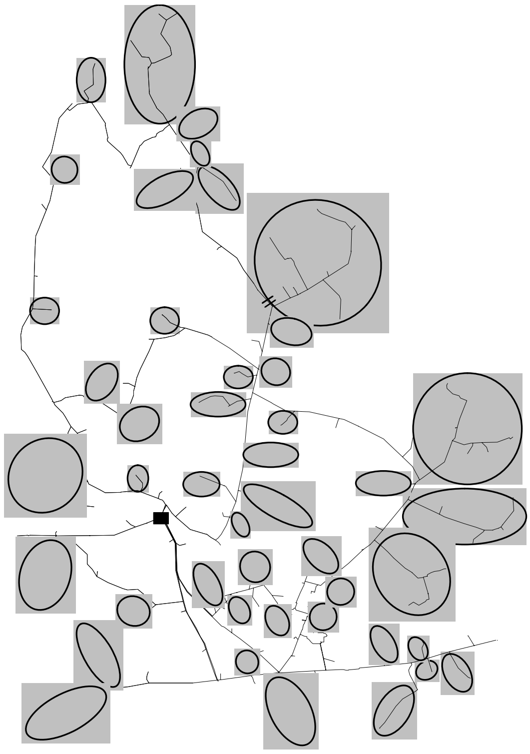

Figure 5.16. Use potential of power electronics (< 300 kW) in a medium-voltage network supplied by a primary substation.

5.2 From visions to implementation

The development tools described in this report can be applied in the implementation of the future networks. At least a part of the network solutions designed and constructed today will be in use in the 2030s and 40s. It is therefore not insignificant, what kind of strategic outlines we establish in the coming years. In the worst case, sticking to the existing technology and design principles would mean that in 30 years time, there would still be nearly 100-year-old operations models in active use. In recent years, more and more positive comments have been established on the new technologies and the benefits of new design principles. Bringing the lines to the roadsides, increasing the amount of covered conductor overhead lines and underground cables, light primary substations, 1000 V systems, and automation have made it possible to improve the reliability of electricity distribution in a cost-efficient way.

Since these new applications are already available and the society sets more stringent requirements for uninterrupted electricity supply, we may justifiably question the fostering of old ideas and traditions in the network development. The basic design principle, namely minimising the total costs (investments, operative costs, outage costs), will remain also in the future, only the weights of cost components and technical solutions will develop along with the overall development in society.

An open-minded approach has been taken to the new technical solutions for instance by Suur-Savon Sähkö Oy, a distribution company that operates in the Finnish Lake District east from the Lake Päijänne and provides electricity for nearly 100 000 customers. The company has pioneered for instance in the development and promotion of the 1000 V low-voltage distribution system. Furthermore, the company has moved 20 kV lines from risky forest areas to roadside, where the lines are less fault prone; it has also used covered conductors and underground cables and constructed light primary substations and light 110 kV supply lines.

Figure 5.17 illustrates some of the effects of new solutions on a medium-voltage feeder. The present construction is illustrated on the left; the feeder is built with overhead lines, and most of the lines are located in forests. The network includes plenty of low-power (< 100 kW) branches. The right-hand illustration shows a renovation scheme: the main line of the feeder is built with underground cables by ploughing to the roadside, and the branch lines are constructed with plastic-covered overhead lines (PAS) or with the 1000 V technology. Branch lines above 100 kW may be implemented as low-voltage DC supply instead of PAS lines. Since we have a long feeder, a 20 kV automated substation is built half-way down the feeder, so that the faults downstream from the substation can be limited to this section by circuit breakers (reclosers) and protection relays.

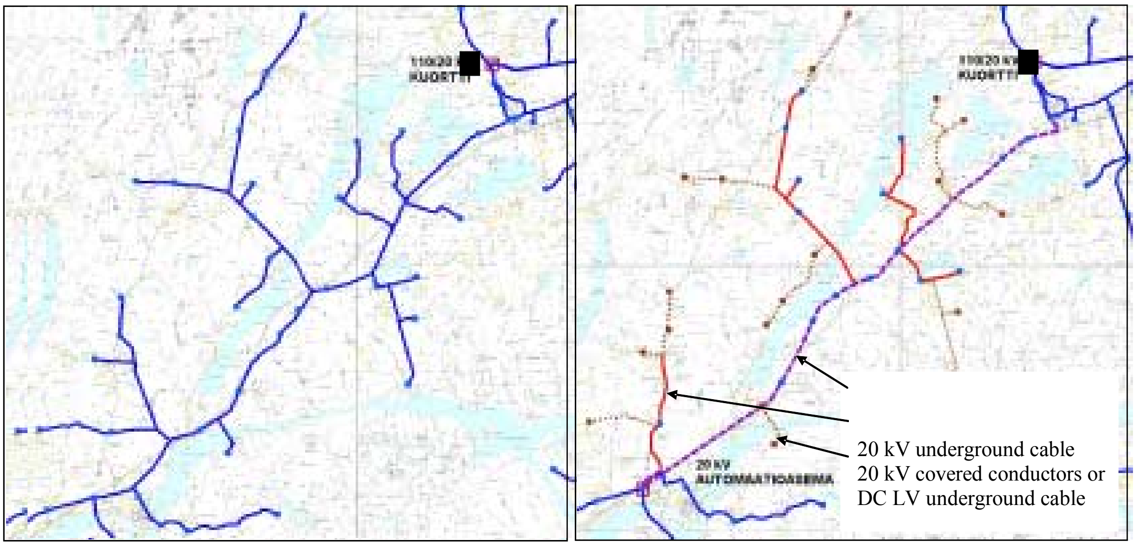

Figure 5.17. Medium-voltage feeder before and after renovation. The main line is built with underground cables by ploughing, the branch lines are built either with 20 kV PAS covered conductors, 1000 V technology, or in the future with DC technology.

6. Future network solutions and their evaluation

This chapter focuses on some candidate visionary networks gathered from various sources during the research project. These visions are put to test in qualitative analysis by evaluating their usefulness and issues related to their implementation. The latter part of the chapter introduces feasibility studies and calculations for different visionary networks. The calculations are based on network data gathered from different electricity distribution companies and on the cost data obtained from manufacturers and the Energy Market Authority.

6.1 Visionary networks in detailed analysis

Next we introduce alternative visionary networks and evaluate their economic feasibility and benefits. The visionary networks are divided into two groups: in urban networks, the division is made according to the method of redundancy in power supply, and the level at which it is implemented. The alternatives are:

Urban Distribution Network 1, redundancy through LV network:

- Meshed LV network
- Several MV supply points (2,3,4…)

Urban Distribution Network 2, redundancy through MV network:

- Radial LV network
- Meshed MV network

Urban Distribution Network 3, DC distribution, redundancy with a backup energy storage:

- DC LV distribution
- Energy storage
- MV network is a radially-operated loop

In rural areas, economical solutions are sought by utilising new voltage levels, DC distribution, and by considering the utilisation of a single-phase system. The alternatives are:

Rural Network 1, three-phase MV network:

- Three-phase MV overhead line network
- MV backup lines with automation
- LV network 400 V, 1000 V, or DC
- If necessary, redundancy with an energy storage as a backup

Rural Network 2, single-phase MV network:

- Single-phase MV network
- Implemented with aerial bundled cable (ABC) or single wire earth return (SWER)
- LV network 230/400 V, conversion from single-phase to three-phase by power electronics

Rural Network 3, two MV voltage levels:

- Three-phase MV overhead network with intermediate voltage (20+6 kV)
- Lower voltage level: ABC or underground cable installed by ploughing
- Short LV network

6.1.1 Urban Distribution Network 1: redundancy through LV network

A meshed low-voltage network supplied from several directions has been in use in many large cities both in Europe and in the USA. A benefit of the meshed structure is that by using similar fuses all over the network, in the occurrence of a fault, only the fuse in the faulted branch will blow. On the other hand, a drawback is that in some cases, blowing of a fuse may remain unnoticed, causing problems only later when another fuse blows because of a new fault.

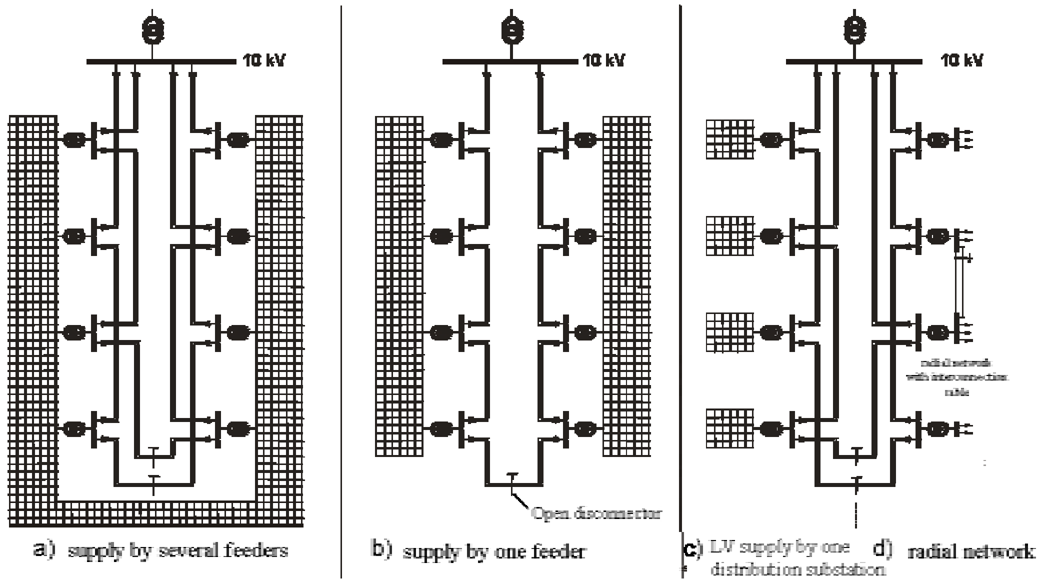

Figure 6.1. Meshed LV network configurations in Germany. (Röstel, T., Presentation to Finnish visitors, HEW, October 2005.)

In the alternative c in Figure 6.1, the LV network is built behind a single transformer, and redundancy concerns only the faults in the LV network. In the alternative b, the power supply is dependent on a single MV line, but a fault in one transformer does not cause an interruption. The highest level of redundancy in power supply is reached in alternative a, where the LV network is supplied by several MV feeders. This is an expensive and heavy configuration, but it is also extremely reliable.

An advantage of the Urban Distribution Network 1 is the high level of reliability. The implementation costs of this concept depend on the amount of reinforcements or changes required in the existing LV network. In completely new target areas, the costs of this solution are lower. A drawback of this solution is the increased need for distribution cabinets; finding places for the cabinets is already now a challenging task in urban environment. An increase in short-circuit currents may also prevent choosing this alternative, as its construction costs become too high.

6.1.2 Urban Distribution Network 2: redundancy through MV network

A solution in which the redundancy in power supply is implemented through medium-voltage network is closest to the present solutions. The principal alternatives are a radially-operated loop provided with a fast switch control in fault situations, and a continuous ring operation, in which the fault situations are cleared with a combination of circuit breakers (reclosers) and relay protection. To avoid voltage sags and short interruptions, a temporary energy storage can be applied.

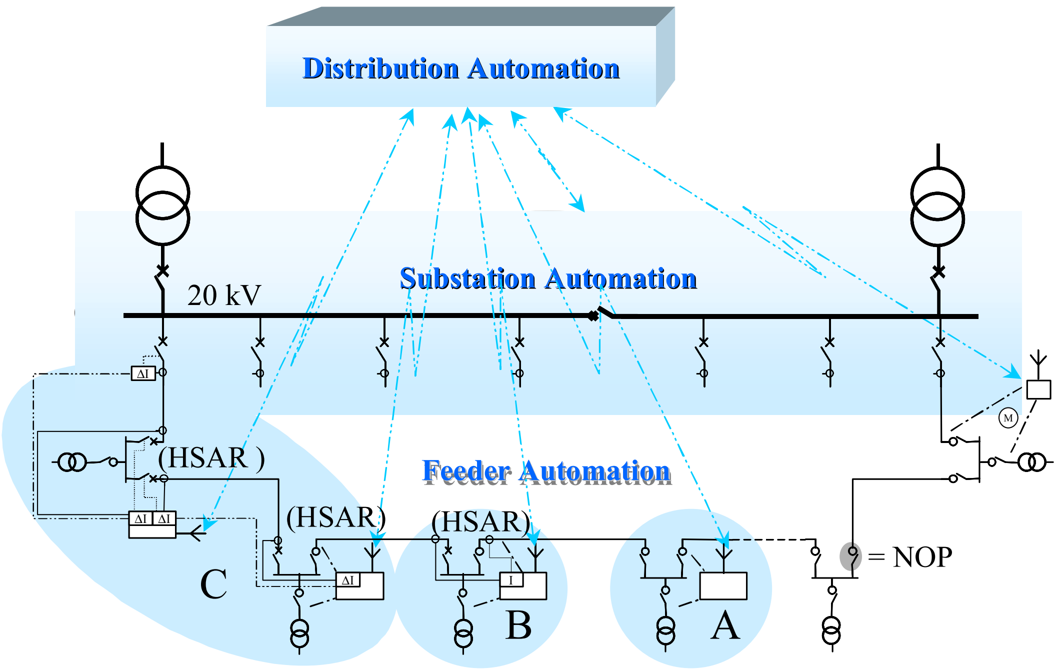

Figure 6.2. Urban distribution network; redundancy provided on the MV side. (Antila, E., Jakeluautomaation kehittäminen keskijänniteverkossa, Diplomityö 2003, TKK. (Developing distributionautomation in medium voltage networks, M.Sc. Thesis, Helsinki University of Technology, 2003))

In the case of a radially-operated loop, in a fault situation, a fast changing of supply can be performed with local automation, if the transformer (distribution substation) in question is located under normal operating conditions at the boundary of a supply section. Otherwise, a relatively fast and reliable data transfer is required to the distribution substations and between them; also reliable fault detectors are needed at the distribution substations. In the occurrence of a fault, due to switching actions, a short interruption in operation will take place. The operating interruption could be avoided in the occurrence of an earth fault, if the network can be operated during an earth fault.

Ring operation requires that the protection is implemented with a differential relay or with a directional comparison protection system. Furthermore, the switches have to be in practice circuit breakers. As an effect of ring operation, voltage sags become more deeper and also their range of influence is larger. Therefore, ring operation does not bring significant benefits compared with a radially-operated, remote-controlled network, unless the system is also protected against voltage sags by a short-term/temporary energy storage. Ultimately, in the economic feasibility comparison, the decision between these two solutions is made based on the costs of the energy storage required for the interruption/voltage sag.

6.1.3 Urban Distribution Network 3: redundancy through DC distribution

The alternative 3 is a modification of the previous concept, where the supply is provided with a backup energy storage in connection with the low-voltage DC distribution. The medium-voltage network is a radially-operated loop backed up by automation. If there is a sufficient energy storage in the DC network, no major requirements are set for the automation of the MV network. The clearing time of MV faults can be optimised between the MV network operation costs and the price of the DC energy storage.

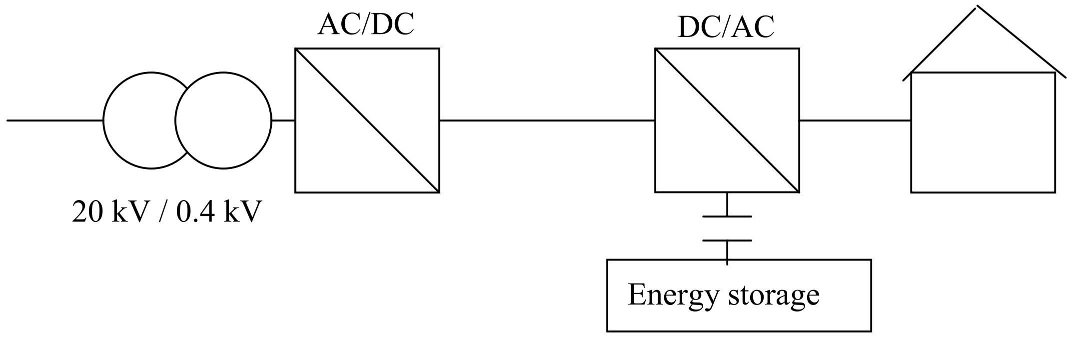

Figure 6.3. Distribution network with DC backup.

Customer-specific redundancy can be achieved by implementing the redundancy of power supply by an energy storage at the transformer on the LV side or at the customer; in practice, this means differentiation of quality.

6.1.4 Rural Network 1: three-phase network

Rural Network 1 is a three-phase radially-operated ring network, in which the reliability of the main line is ensured by careful design of the line route and by network automation. The objective is to connect critical loads close to the main line and to limit outage durations by remote control of switches and fault detectors. At the beginning of branch lines, there are usually remote-controlled disconnectors. The LV network is implemented either with a 1000 V AC or DC solution. Medium-voltage feeders, on which the loads are light and no significant load growth is expected, have been replaced by a 1000 V low-voltage system.

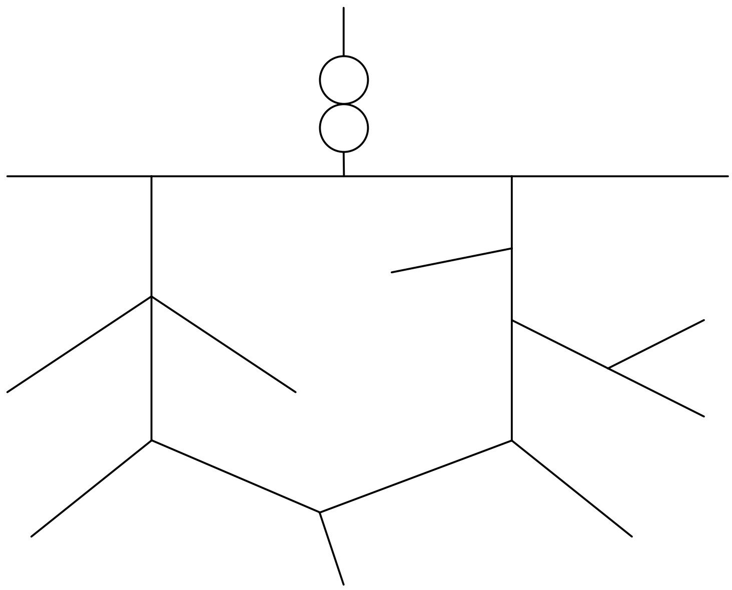

Figure 6.4. Principle of Rural Network 1. The main line is a radially-operated loop.

Considering the line structures for a MV network, an overhead line is a possible alternative in cases where forests or trees are not expected to cause disturbances. A covered conductor reduces the disturbances caused by tree branches or birds, yet this conductor type is problematic in large disturbances caused by climatic conditions. Without detection of tree contact, it does not provide significant benefits in forest areas. The best level of reliability is reached with underground cabling of the MV network; however, with the present technology, this is an expensive solution especially if the soil is stony and cables cannot be installed by ploughing.

Power quality can be improved by network automation in the case of individual faults. In the case of a severe failure, however, more crucial is how well the network can withstand the stresses caused by severe weather conditions and how fast the network can be repaired and restored to operating condition after a fault. This can be affected to some degree by the selection of line routes; in any case, a part of the network has to be built in areas where the line constructions have to be tree-proof, that is, protected against risks caused by trees.

Rural Network 1 is a very potential future network solution. Targets for further development are:

- Fault detection methods for faults developing in covered conductors
- Development of large-scale network automation
- Development of tree-proof overhead line structures.

6.1.5 Rural Network 2: single-phase MV network

The chief purpose of Rural Network 2 concept is to evaluate the use of a single-phase MV network; a single-phase system is widely used for instance in the USA. Consequently, the low-voltage network is smaller in scale and the distribution substations are smaller, supplying only one or a few customers. The network can be built cost-efficiently also by applying single-phase aerial bundled cables.

Advantages of a single-phase medium-voltage network are the lower construction costs, a narrower line path and easier use of aerial bundled cables. In Finland, however, a problem is that the customers are accustomed to the three-phase supply. This limits the single-phase system to new construction targets; an alternative is conversion from the single-phase to three-phase system by inversion at the customer interface.

In the single-phase system, a further problem may also be the voltage rise caused by the current of the return conductor. To prevent this, a more efficient earthing would be required, or the touch voltage protection of the network should be developed further to ensure that this voltage is not harmful or hazardous. In the Finnish earthing conditions, the latter seems to be a more realistic alternative.

6.1.6 Rural Network 3: two MV voltage levels

Finally, we discuss the opportunity of using more than one medium-voltage level. Solutions of this kind are in current use for instance in Great Britain (33/11 kV). The investigation is based on the network, where the main line that constitutes a ring would be implemented at a higher voltage level (20, 30, or 45 kV). To reach the maximum reliability, it would be built by applying automation and tree-proof structures. The branch lines would be implemented at a lower MV level (3.6 or 10 kV), in which case they would comprise separate sections (sectionalisation). Selecting conductors with small cross-sections would enable the installation by ploughing. Implementing the branches of the MV network at a lower voltage level would even replace a part of the low-voltage network.

An opportunity is to replace the present 20 kV overhead line with a 45 kV covered conductor, which, when implemented as a Slim Line type construction could fit the present line path. A line of this kind could be used to supply satellite-type primary substations.

In Finland, the distribution network solutions have traditionally been simple and clear-cut, and hence there is not necessarily willingness to adopt more medium-voltage levels. On the other hand, with a 20 kV overhead line, it is possible to transmit relatively large powers, and therefore there is no obvious need to raise the voltage level.

6.1.7 Summary

In the case of the urban distribution network, the most realistic solution seems to be an alternative in which the redundancy of power supply is implemented by network automation on the MV side so that the network is radially operated in normal operating conditions. It would be advantageous to develop the concept further so that also a short-term operation of the network during an earth fault would be possible; in that case, single-phase faults would not cause an interruption to the customers.

This same logic could also be applied to the development of rural networks; the design could be based on the alternative number four, where the MV main line is constructed as reliable and secure as possible and the branches are sectionalised. In rural areas, severe weather conditions, storms, and snow loads are significant factors, and therefore the MV network technology should be developed accordingly towards tree-proof structures. Furthermore, the economic feasibility of the single-phase MV distribution should be analysed. The development of power electronics enables the conversion from single-phase to three-phase at a reasonable price; this will remove the major technical obstacle from the utilisation of single-phase MV distribution.

6.2 Evaluation of the economic feasibility of network alternatives

6.2.1 On methods and tools applied in economic feasibility calculations

For the economic feasibility calculations for visionary networks, a software tool ”Evaluation concept” (Evaluaatiokonsepti) was generated. The basic idea behind the tool is to generate an optimal distribution network for a given area based on certain raw data; this enables an easy and objective comparison of different network alternatives.

The basic principles of the calculation model are as follows:

- Pareto curves (Willis 2004) are calculated for the selected sets of conductor types, primary substations, and distribution substations; these curves describe the present value of the costs of the optimal design, with transferred power as a parameter (Figure 6.5).
- The loads are represented as an evenly distributed grid, taking however into account that some of the distribution substations are owned by customers (no respective LV network); also the proportion of constructed land to the non-planned area has to be taken into account.

- The optimal sizes for the transforming district and primary substation are determined with the radius R of the LV or MV distribution network around the transformer as a parameter.
- The optimal number of manually controlled disconnectors is calculated by using the outage costs of electricity distribution. The outage costs and the SAIFI and SAIDI reliability indices are estimated for the basic case and solutions with 1) remote-controlled disconnectors and also 2) fault detectors.

When calculating the Pareto curves, not only the investment and loss costs but also costs related to land use, buildings, maintenance, and environmental factors are taken into account. In urban areas in particular, the factors associated with environment and construction constitute a significant proportion of the total costs. The costs of line structures, installation, excavation, distribution and primary substation instrumentation, and land use were calculated chiefly by applying the catalogue ”Verkkokomponentit ja indeksikorjatut yksikköhinnat vuodelle 2005” (Network components and index-corrected unit prices for 2005) published by the Energy Market Authority (EMA).

The calculation parameters were:

- Lifetime 20 years
- Interest rate 5 %
- Loss price 10 c/kWh

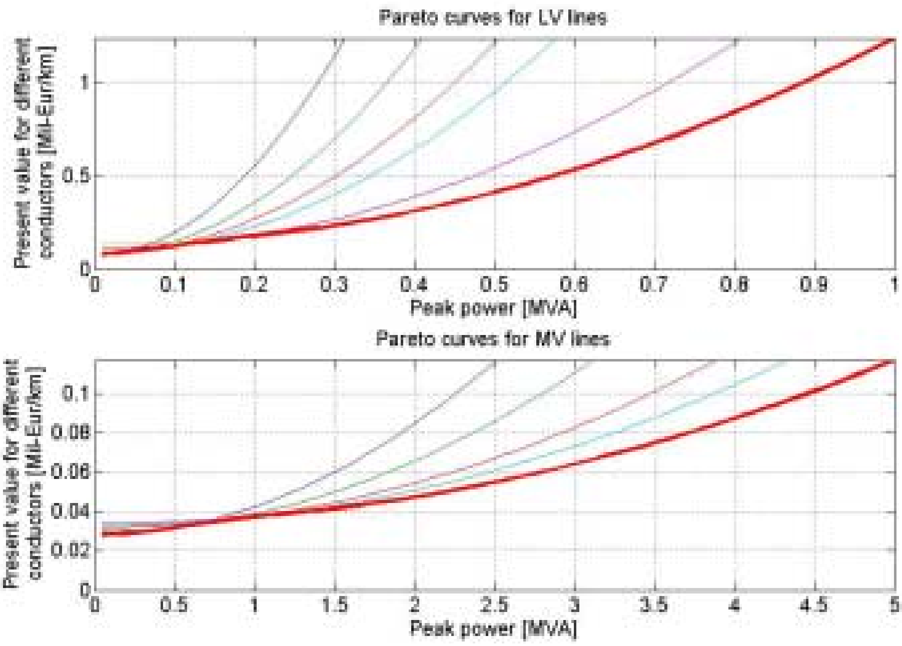

Figure 6.5. Pareto curves for LV and MV lines. On the horizontal axis: peak power MVA during the first year. Vertical axis: present value of total costs M€/km. In the LV network, the selected conductor types are underground cables: 70, 120, 185, 240, and 2*240 and 3*240 mm^2. Correspondingly the MV conductor types are Sparrow, Raven, Pigeon, Suursavo and Al132.

The calculations were made both for two rural network cases and two urban network cases. The calculations were based on the following data on the loads:

- Load density in the rural area 0.03 or 2 MW/km^2
- Load density in the urban area 5 or 40 MW/km^2

- Distribution of customer groups (%) in rural and urban areas, respectively
    - Residential 45 and 40
    - Agriculture 10 and 0
    - Services 10 and 13
    - Public 15 and 27
    - Industry 20 and 30
- Outage costs €/kWh
    - Residential 3
    - Agriculture 3
    - Services 4
    - Public 5
    - Industry 7

6.2.2 Calculation results

Rural networks

The first task was to investigate the effects of voltage levels on the network costs in a rural area. The initial assumption was that on the MV side, the network was constructed with overhead lines, and on the LV side, with aerial bundled cables. The primary substations were assumed to be built on open land, and the distribution substations were pole mounted. The calculation results with the load density of 0.03 MW/km^2 are presented in Table 6.1. and with the load density of 2 MW/km^2 in Table 6.2.

The results show that it is not economically profitable to change the voltage level of the MV network from the present 20 kV. Were the voltage level lowered to 10 kV, the losses would increase, and the radius around the primary substation could be only about 70 % of the present network. Correspondingly, the supply area of the primary substation would be 50 % and the primary substation density would be double of the present values. Changing over to higher voltages (30 kV) instead would reduce losses, yet it would require broader line paths, unless covered conductors are used. Raising the voltage level would not be an economical solution, except maybe in the case of the highest load densities.

The economic feasibility of the 1 kV low-voltage system has been analysed in the right-hand column of Tables 6.1 and 6.2. The calculations are based on the assumption that the whole 400 V network is replaced with a 1000 V solution. Using 1000 V in the LV network reduces the costs of both the LV and MV network. In the LV network, savings are achieved by the decreased losses and by the fact the geographical area of transforming districts can be larger. For the same reason, the line lengths in MV become shorter. In the 1000 V system however, additional costs are caused by an extra 1000/400 V transformer (Lohjala 2005). Using a 20/1 kV system is hence profitable when the load density is low and the number of load points per square kilometre is small.

Next, the economic feasibility of network automation in 20 kV overhead networks was analysed. The results for different load densities are presented in Tables 6.3 and 6.4. For outage cost values, only the variable costs (€/kWh) were used, since the network automation can influence only the duration of outages, not their occurrence rate. The selected outage cost values (cf. section 6.3.1) represent the lower end of the range of variation in Table 6.1, the calculation results being hence very conservative. The conservativeness is further increased by the fact that the expected future growth in outage cost values is not taken into account.

Table 6.1. Effect of voltage level on the network costs and the network structure in rural areas at different voltage levels. Overhead line network with average peak load 0.03 MW/km^2 (includes procurement costs and no-load losses).

Costs and network structure	10 kV +400V	20 kV +400V	30 kV +400V	20 kV +1000V
LV network costs (k€/km^2) - conductors - distribution substations - 1.0/0.4 kV transformers*	 27.1 6.3	 27.1 6.3	 27.1 6.3	 18.3 2.9 17.9
MV network costs (k€/km^2) - conductors - primary substations	 24.7 3.0	 25.1 1.8	 30.3 1.8	 16.8 1.7
Total network costs Present value (k€/km^2)	 61.1	 60.3	 65.5	 57.6
Line lengths (km/km^2) - low-voltage lines - medium-voltage lines	 1.13 0.89	 1.13 0.83	 1.13 0.83	 0.86 0.51
Radius of the supply area (km) - LV distribution substations - MV primary substations	 0.72 11.6	 0.72 16.8	 0.72 16.8	 1.3 18.3

Table 6.2. Effect of voltage level on the network costs and the network structure in rural areas at different voltage levels. Overhead line network with a high load density 2 MW/km^2 (includes procurement costs and no-load losses).

Costs and network structure	10 kV +400V	20 kV +400V	30 kV +400V	20 kV +1000V
LV network costs (k€/km^2) - conductors - distribution substations - 1.0/0.4 kV transformers*	 265 61	 265 61	 265 61	 178 61 365
MV network costs (k€/km^2) - conductors - primary substations	 115 43	 73 25	 62 19	 67 24
Total network costs Present value (k€/km^2)	 484	 423	 407	 695
Line lengths (km/km^2) - low-voltage lines - medium-voltage lines	 4.2 2.96	 4.2 1.96	 4.2 1.62	 2.96 1.82
Radius of the supply area (km) - LV distribution substations - MV primary substations	 0.5 5.41	 0.5 7.16	 0.5 8.0	 0.59 7.3

Table 6.3. Effect of automation on total network costs in a 20 kV overhead line network with a low load density 0.03 MW/km². There are six controlled disconnector substations and six fault detectors per primary substation (R = 16.8 km).

Automation functions:	Manually controlled disconnectors	Remote-controlled disconnectors	Plus fault detectors
SAIFI (1/a)	8.39	8.39	8.39
SAIDI (hrs/a)	46.9	1.9	1.4
Outage cost (k€/km²)	66.	2.6	2.0
Difference of the outage cost	-	63.4	64.0
Investment, present value (k€/km²)	0.5	2.3	2.4
Difference of investment (k€/km²)	-	1.8	1.9

Table 6.4. Effect of automation on total network costs in a 20 kV overhead line network with a load density 2 MW/km². There are six controlled disconnector substations and 14 fault detectors per primary substation (R = 7.16 km).

Automation functions:	Manually controlled disconnectors	Remote-controlled disconnectors	Plus fault detectors
SAIFI (1/a)	1.009	1.009	1.009
SAIDI (hrs/a)	0.75	0.19	0.115
Outage cost (k€/km²)	74.8	18.7	11.4
Difference of the outage cost	-	56.1	63.4
Investment, present value (k€/km²)	7.4	9.92	12.25
Difference of investment (k€/km²)	-	2.52	4.854

The economic feasibility of network automation was analysed by two cases: the remote control of disconnectors and application of fault detectors. The assumption was that fault detectors were placed at such branching points of the line, which are not favourable positions for the remote control of disconnectors. The values of Tables 6.3 and 6.4 represent an optimal scope of automation. The return/cost ratio of the investment is extremely high, varying between 13 and 35.

The next task was to analyse the economic feasibility of single-phase MV distribution. The results are shown in Table 6.5. The 20 kV three-phase overhead line system was compared with a single-phase aerial cable network. The LV network was similar in both cases. According to the calculation results, with both load densities, the implementation of the MV network with single-phase aerial cable would clearly be a lower-cost solution. The costs of fault situations were neglected in the calculations; these might make the single-phase solutions an even more preferable solution.

A problem of the single-phase solution is that the low-voltage supply for customer needs has to be implemented as a three-phase arrangement. Conversion from single-phase to three-phase supply is nowadays possible by the means of power electronics, the costs being in the range of 100 €/kW. This increases the total costs of the single-phase MV solution making it an unprofitable alternative.

Table 6.5. Comparison of single-phase and three-phase distribution system. 1-phase system implemented with a 20 kV aerial cable, and 3-phase system with 20 kV overhead line. In both cases, the LV network is built with 400 V aerial bundled cable. Load density is 2 or 0.03 MW/km^2.

Costs and network structure	20 kV 1-phase 2 MW	20 kV 3-phase 2 MW	20 kV 1-phase 0.3 MW	20 kV 3-phase 0.03 MW
LV network costs (k€/km^2)				
- conductors	265	265	27.1	27.1
- distribution substations	61	61	6.3	6.3
- 1-phase/3-phase conversion	200		10	
MV network costs (k€/km^2)				
- conductors	55	73	19.3	25.1
- primary substations	20	25	1.4	1.8
Total network costs				
Present value (k€/km^2)	601	423	64.1	60.3
Without 1-phase/3-phase conversion	*401*		*54.1*	
Line lengths (km/km^2)				
- low-voltage lines	4.2	4.2	1.13	1.13
- medium-voltage lines	1.8	1.96	0.81	0.83
Radius of the supply area (km)				
- LV distribution substations	0.5	0.5	0.72	0.72
- MV primary substations	8.0	7.16	21.0	16.8

Urban networks

When evaluating urban networks, the assumption is that they are constructed completely as underground cable systems. In the calculations, it is assumed that the distribution substations are mounted in existing buildings, while primary substations are housed in buildings of their own. The effect of voltage level on the total costs of MV network in urban networks is illustrated in Tables 6.6 and 6.7. The analysed cases corresponded to the load densities of 5 and 40 MW/km^2.

According to the results, raising the voltage level reduces the costs of MV network particularly in heavily loaded networks. It was assumed in the calculations that the cable installation costs are equal irrespective of the voltage level. If the procurement cost of a 20 kV cable is taken as the reference, the 10 kV cable of the same cross-section costs about 85 % and a 30 kV cable about 120 % of the 20 kV cable.

The proportion of the low-voltage network is about a half of the total network costs. The relative proportion of distribution and primary substations is somewhat larger than in the rural areas. The costs of Tables 6.6 and 6.7 are calculated based on the data provided by the EMA. In large cities, such as in Helsinki, the construction costs associated with primary and distribution substation buildings are higher than this.

Table 6.6. Effect of voltage level on the network costs and the network structure in urban areas. Underground cable network with an average peak load of 5 MW/km^2.

Costs and network structure	10 kV	20 kV	30 kV
LV network costs (k€/km^2) - conductors - distribution substations	 1157 252	 1157 252	 1157 252
MV network costs (k€/km^2) - conductors - primary substations	 493 162	 368 162	 356 162
Total network costs Present value (k€/km^2)	 2064	 1939	 1927
Line lengths (km/km^2) - low-voltage lines - medium-voltage lines	 9.4 2.9	 9.4 2.9	 9.4 2.9
Radius of the supply area (km) - LV distribution substations - MV primary substations	 0.25 2.5	 0.25 2.5	 0.25 2.5

Table 6.7. Effect of voltage level on the network costs and the network structure in urban areas. Underground cable network with high load density 40 MW/km^2.

Costs and network structure	10 kV	20 kV	30 kV
LV network costs (k€/km^2) - conductors - distribution substations	 5251 1074	 5251 1074	 5251 1074
MV network costs (k€/km^2) - conductors - primary substations	 1403 558	 800 558	 649 558
Total network costs Present value (k€/km^2)	 8286	 7683	 7532
Line lengths (km/km^2) - low-voltage lines - medium-voltage lines	 43 6.8	 43 5.4	 43 4.8
Radius of the supply area (km) - LV distribution substations - MV primary substations	 0.15 1.5	 0.15 1.5	 0.15 1.5

Table 6.8. Effect of automation on total network costs in a 10 kV urban cable network with a load density of 5 MW/km^2.

Automation functions:	Manually controlled disconnectors	Remote-controlled disconnectors	Plus fault detectors
SAIFI (1/a)	0.74	0.74	0.74
SAIDI (hrs/a)	0.41	0.13	0.08
Outage cost (k€/km^2)	114	36	22
Difference of the outage cost	-	78	92
Investment, present value (k€/km^2)	15.3	16.4	20.5
Difference of investment (k€/km^2)	-	1.1	5.2

Table 6.9. Effect of automation on total network costs in a 10 kV urban cable network with a load density of 40 MW/km^2.

Automation functions:	Manually controlled disconnectors	Remote-controlled disconnectors	Plus fault detectors
SAIFI (1/a)	0.4	0.4	0.4
SAIDI (hrs/a)	0.11	0.076	0.055
Outage cost (k€/km^2)	238	169	126
Difference of the outage cost	-	69	112
Investment, present value (k€/km^2)	23.2	33.2	46.2
Difference of investment (k€/km^2)	-	10.0	23.0

The economic feasibility of network automation was analysed in urban circumstances with the same principles as in the rural areas. The results are shown in Tables 6.8 and 6.9. In urban conditions, the electricity distribution is quite reliable already; the calculated average outage duration experienced by a customer is only 7 minutes even without automation. In spite of this, due to high load density, network automation and especially remote reading of fault detectors is profitable.

The redundancy of power supply through LV network was not analysed with this calculation model. The reason is that with the calculation model based on average values, it is difficult to estimate the actual need for reinforcements in the LV network. However, if the redundancy through LV network requires construction of additional lines, in the light of Tables 6.6 and 6.7, it does not seem to be profitable; instead, an investment in the MV network automation would be a more profitable solution for the purpose.

According to the estimates and calculations, it is not economically profitable to change the voltage level of MV network from the present 20 kV solution. The reliability of supply can be improved by network automation. In overhead line networks, this is very profitable; in particular, with respect to remotely read fault detectors, this is economically justifiable also in urban cable networks.

A single-phase MV distribution system is economically justifiable, if the customers can be provided with single-phase supply, or if the cost development of power electronics offers a cost-efficient way to convert single-phase supply to three-phase one.

In an urban distribution network, the most profitable solution is probably to arrange the redundancy of power supply on the MV network side.

6.2.3 Another cost analysis for network solutions (Matikainen 2006, Partanen et al. 2006)

The cost effects of different network technologies on the development of electricity distribution networks have been evaluated and illustrated by five network strategies. The first strategy, renovation with the current technology, has been used as a baseline in comparisons. In other strategies, the methods involving moving the power lines to roadsides, covered conductors, 1000 V low-voltage technology, underground cabling, or light primary substations have been applied to varying degree.

The cost analysis is based on a network section of the distribution network operator Suur-Savon Sähkö Oy; the section covers 14 000 customers. The distribution network is built as an overhead line construction, and 64 % of the line length is located in forest areas, where the fault risk is higher. Only 2 % of the 1000-km-long 20 kV network and 7 % of the low-voltage network are built as underground cable networks. Figure 6.6 illustrates the total costs of different investment strategies.

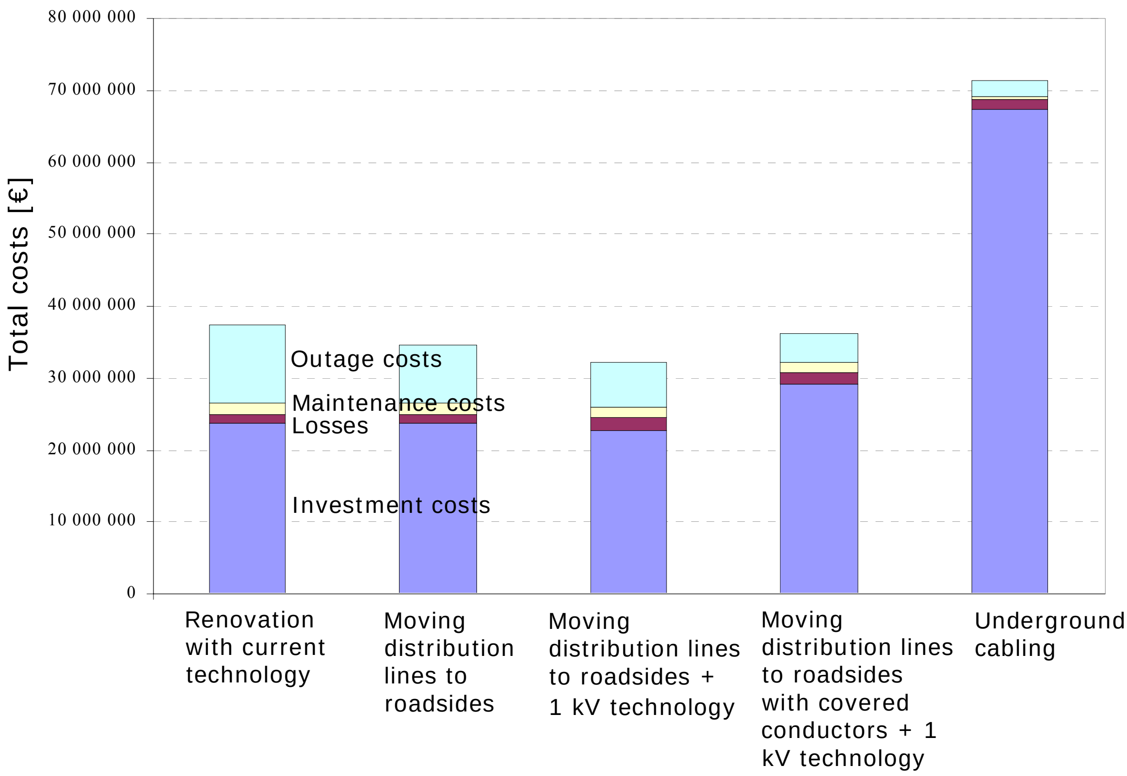

Figure 6.6. Costs of various investment strategies divided into investment, loss, maintenance and outage costs.

The analyses show that an "optimum network" includes several new but also existing technical solutions. A network strategy based on a single technology, such as overall underground cabling of the network, cannot be considered a reasonable economic solution. In an optimum network, the socio-economic costs are kept to minimum, the reliability of the network is notably better than at present and the susceptibility to blackouts is smaller. From the end-customer point of view, in addition to reliability, it is naturally interesting to know how the strategy influences the transmission tariffs. The development of transmission price will in fact be steady, if the investments are made during a long period of time, for instance in 20–40 years, and the depreciations and capital financing costs will stay at the present level. If the transition from the present network to the optimum network is carried out fast, for instance in ten years, the financing costs will grow considerably, which will lead to raises in transmission tariffs.

As the reliability of supply and susceptibility to blackouts are emphasised, also underground cabling becomes a viable alternative in certain cases. However, in this solution, depreciations and financing costs will be notably higher and there will significant increases in transmission prices, particularly if the transition from overhead lines to underground cables is implemented in a short period of time. The reliability of the underground cable network will be excellent especially with respect to blackouts.

Figure 6.7 shows how a change in the valuation of outage costs influences the costs of different investment strategies. The present level of outage costs is 100 %. In Finland, the outage cost values have approximately doubled in the past ten years.

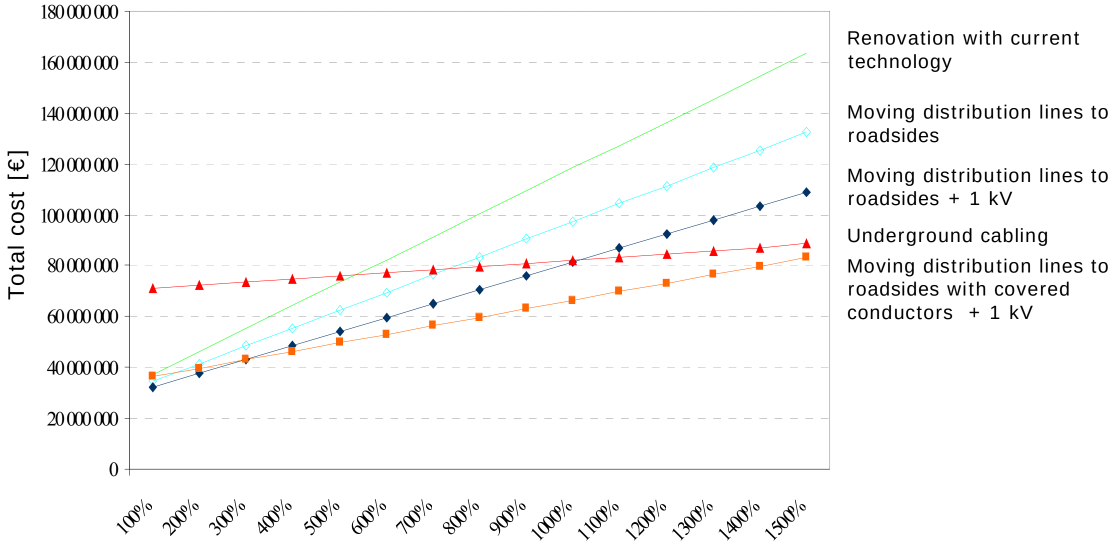

Figure 6.7. Effects of changes in the valuation of outage costs on the total costs of different investment alternatives (100 % = present level of outage costs).

The above figure shows that if the networks are renovated with the present technology, the cost optimum will never be reached. On the other hand, even if the valuation of outage costs were ten-fold, a full-scale underground cabling would not be justified. Hence, one of the key results of the analysis is that an optimum solution is reached by utilising a set of methods and technologies in the development of distribution networks. It is also worth noticing that the suggested cost analysis for network strategies is not universal, but the cost analysis has to be performed for each case individually. Also the mutual ratios between the costs will probably change, which in turn will affect the economic feasibility comparisons between the network strategies. In all cases, it is worth considering whether the best result is achieved by focusing on automation solutions or by concentrating on the development and utilisation of primary technology.

7. Visionary network

7.1 Objectives set for future distribution networks

Essentially improved reliability is expected of future electricity distribution networks. This means both an improvement in average statistical reliability and a significant decrease in the susceptibility to a risk of long-term, large disturbances. The reliability requirement will probably be divided into a number of quality classes, for instance according to the customer group, load density, or location. In addition to network technology, the customers' power supply can be secured by local redundancy, the need for which will increase in the future; there will also be a wider selection of technical solutions for the purpose. In addition to the differentiation of power quality, also the price differentiation may become possible: better-quality electricity at extra price.

Improving network reliability requires investments, while the electricity distribution business faces demands for improved cost-efficiency. The future regulation also involves various uncertainty factors; however, it is highly likely that the regulation will take the reliability aspect into account.

Environmental aspects will play an increasingly important role in planning the future distribution networks. This concerns several issues, such as landscape values, land use, electric and magnetic fields, and substances detrimental to environment.

The future also includes major uncertainty factors, such as a possible strong boom in distributed generation; this will call for flexibility in distribution networks.

7.2 Visionary network in rural areas

The large need for renovation and reinforcement in rural networks together with intensified reliability expectations provide an opportunity for radical modernisation of distribution networks. This view of the need for significant modernisation is also supported by the changes in the operational environment.

At the moment, the medium-voltage network is the most vulnerable part of the distribution network; most of the interruption duration experienced by customers is caused by disturbances in the medium-voltage network. At present, overhead lines account for 90 % of the total of 140 000 km of the Finnish medium voltage network. All the known overhead line constructions are susceptible to disturbances caused by adverse weather conditions, such as storms and thunder. In the case of overhead lines, the line structures are exposed to a risk of destruction, which may at worst lead to large disturbances and extremely long supply outages. It is estimated that the climate change would result in 1.5-fold failure rates compared to the present rate. Further, the wood poles, on which the overhead lines are mounted, are ageing. Also the restrictions on the use of impregnants support the reduced use of wood poles. Finally, as the landscape values will be emphasised, acquiring land for line paths will be more difficult, and their prices will grow.

The above issues and the expected development of cables and cabling methods, together with a probable decrease in costs resulting from the demand in starting extensive cabling projects will promote underground cabling as a key method in the renovation of rural networks and improvement of reliability. In particular, cabling is supported by the efforts to reduce the network's susceptibility to weather-induced blackouts. This holds both for medium- and low-voltage networks, where the development of installation methods has made the cable network even a lower-cost alternative than the overhead line network. In the development of cabling technology, it is advisable to consider the solutions developed elsewhere in the world.

Cabling of medium-voltage network considerably increases earth fault currents, which may force to the compensation of earth fault current. Among the advantages of compensation, in turn, is the reduction in reclosings. Very large-scale cabling may require distributed compensation and new solutions for earth fault protection.

In particular, the underground cabling of the main lines of medium-voltage network is considered a solution of the future main lines. Also an opportunity to install the underground cables to the roadsides would probably reduce the installation costs and speed up fault repair. Due to the inherently long repair times of cables, the main part of the cable sections should be provided with redundant interconnections. Supply outages can also be shortened by backup power connected to the network. The importance of this solution will increase in the future.

In Finland, there are plenty of areas where underground cabling is difficult to implement with conventional methods. For these areas, a weather- and tree-proof new overhead line construction would be welcome. Also mechanically protected surface mounting of cables may prove a feasible solution. Plastic-covered conductors may retain their position in roadside line constructions, particularly, if a fault detection system can be developed for faults evolving in the conductors. However, considering blackouts caused by storms and falling trees, a covered conductor solution always involves a risk.

Another specific feature in the Finnish distribution networks has been the large protection zones in rural areas. Light primary substations can reduce the range of influence of faults. Their economic feasibility will probably be increased by the light transmission line structure that will be taken into use in the future. Also the use of sectionalising circuit breakers that are common in other countries is a very efficient way to reduce the range of influence of faults, especially if a significant load is concentrated at the beginning of the feeder.

A particularly efficient basic solution to improve reliability would be to construct branch lines as protection zones of their own. This provides further justification for the application of 1 kV low-voltage technology; other potential future technologies can be a light circuit breaker (recloser) of the branch line, microgrid and DC distribution. Also a combination of a fault detector and a remote-controlled disconnector mounted at the beginning of the branch line can be a means to significantly reduce outage times.

The chart in Figure 7.1 illustrates the development needs in rural areas. The chart also includes the rationale for the presented solutions, based on the evaluation of the present state and operational environment.

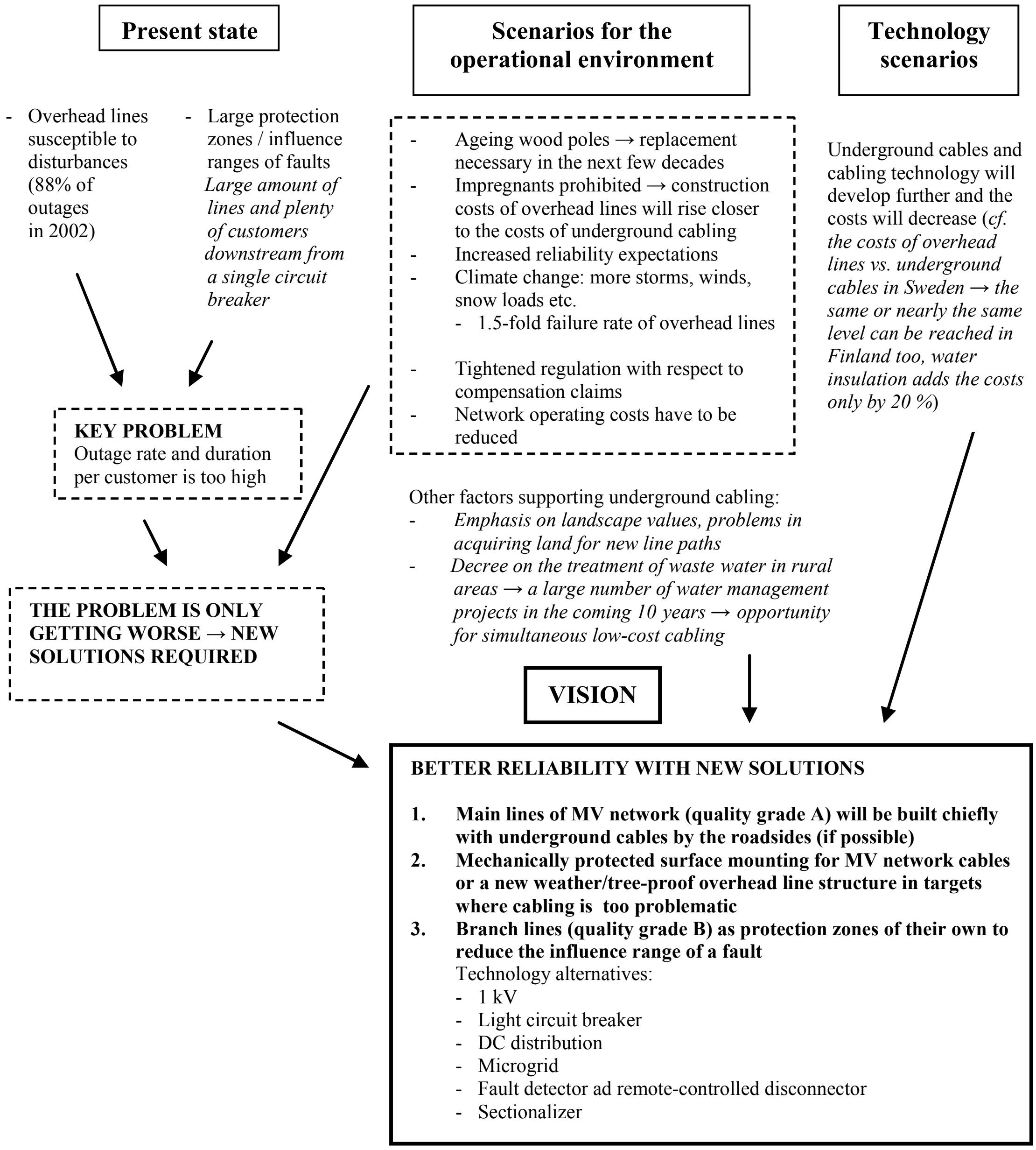

Figure 7.1. Improving the reliability of rural networks by new structural solutions.

Communication technology has developed rapidly, and this tendency is expected to continue also in the future. The technology becomes faster and more reliable;

simultaneously, international standardisation promotes the compatibility of systems and aims at ensuring improved data security. Standardised, reliable, real-time data transfer between devices and control systems enables the realisation of essentially more advanced network automation. In fault detection, both fault detection algorithms and fault detectors equipped with new sensor technology and data transmission capabilities will probably be utilised in future.

In Finland, there is little electricity generation connected to the distribution networks so far. It depends highly on the political decision-making and the price development of energy and associated technology, how common the small-scale generation will become. The present trend in the EU politics is to strongly support distributed generation, and also in Finland, there are parallel political decisions under way. The increasing distributed generation will complicate the system, which may make the network voltage control and protection issues more difficult. A further negative aspect involved in distributed generation is that it reduces the amount of energy transmitted through the network and thereby also the transmission revenue. Consequently, there will be fewer resources available for the maintenance and development of the network. Nevertheless, when considering distribution network design, scaling down the network (reducing the network dimensions) is hardly possible by basing the network on distributed generation.

Large-scale adoption of distributed generation may require that the distribution management system (DMS) is extended to consumers. For this purpose, a system of Automated Meter Management (AMM) is being developed. Data transfer between the consumer and distribution management system will be bidirectional, and consumption can be controlled to enable efficient active management of the network (for instance voltage control and fault situations) and to improve the utilisation rate of the transmission capacity. In the long term, the reliability of the system and the electricity quality can probably be improved by applying distributed energy resources; this presupposes the development of islanding.

If we wish to take advantage of the opportunities provided by increased distributed generation in low-voltage networks and the development of energy storages to improve the reliability and quality of electricity distribution, microgrid networks will be required. Microgrid is a subsystem of a low-voltage distribution network that includes local generation and associated loads and, if necessary, an ability to island operation. It also includes at least one energy storage. On the other hand, microgrid networks could be applied like a controlled load in the active management of the distribution network; in other words, they could be used for the voltage control and to release transfer capacity in the same way as is done with individual consumers with the help of AMM.

Figure 7.2 presents a long-term view of the opportunities of distributed energy resources in improving the quality of electricity supply.

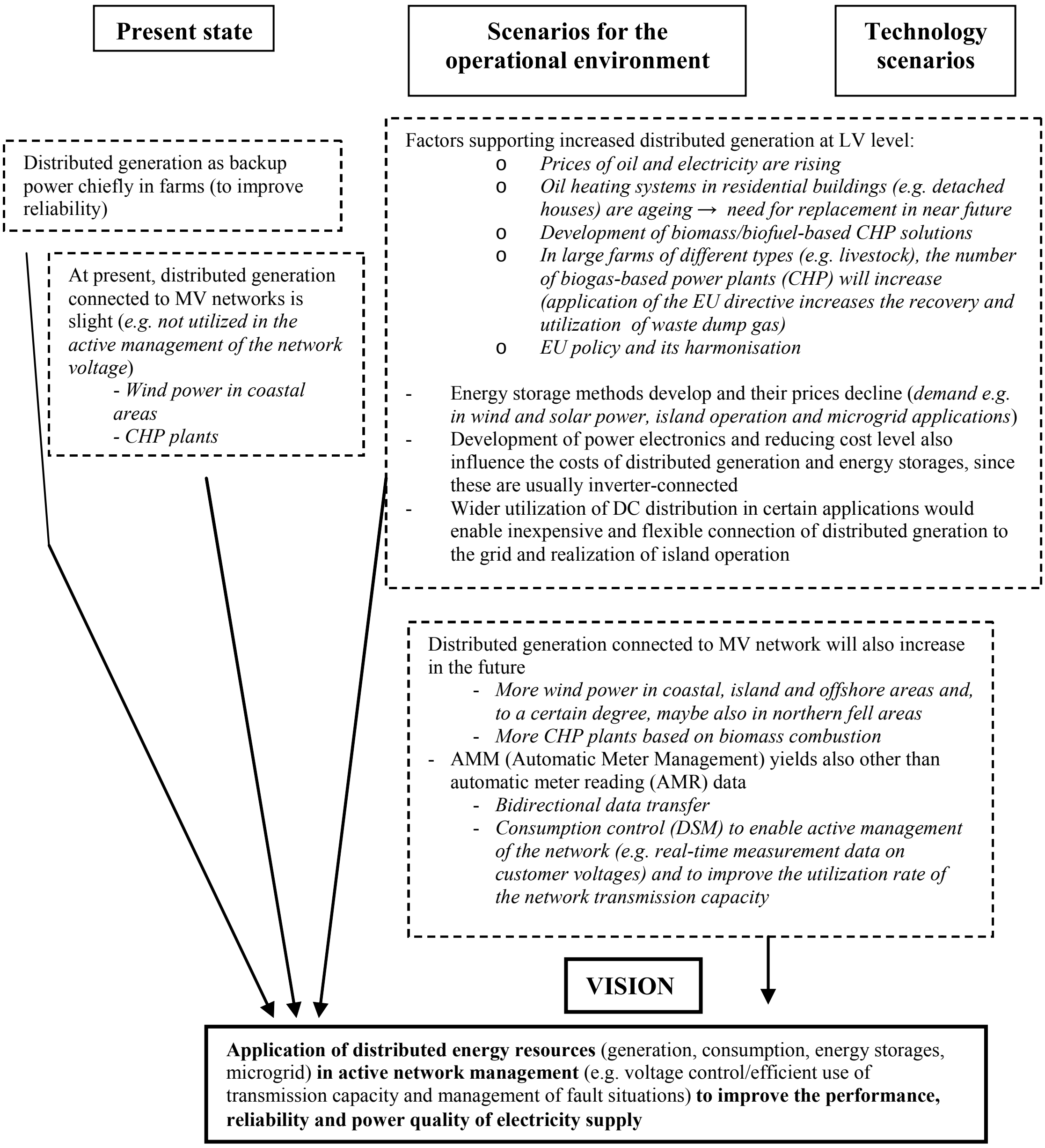

Figure 7.2. Distributed energy resources to improve the network reliability and power quality.

Large-scale application of power electronics to electricity distribution seems an interesting alternative. In the long term, it may be possible to apply components implemented with semiconductor technology to replace conventional components, such as transformers and circuit breakers. Like the 1000 V low-voltage system, DC distribution may also bring novel low-voltage network solutions and opportunities for replacing medium-voltage branches.

Figure 7.3 summarises the above-discussed Visionary Network 2030 for rural areas.

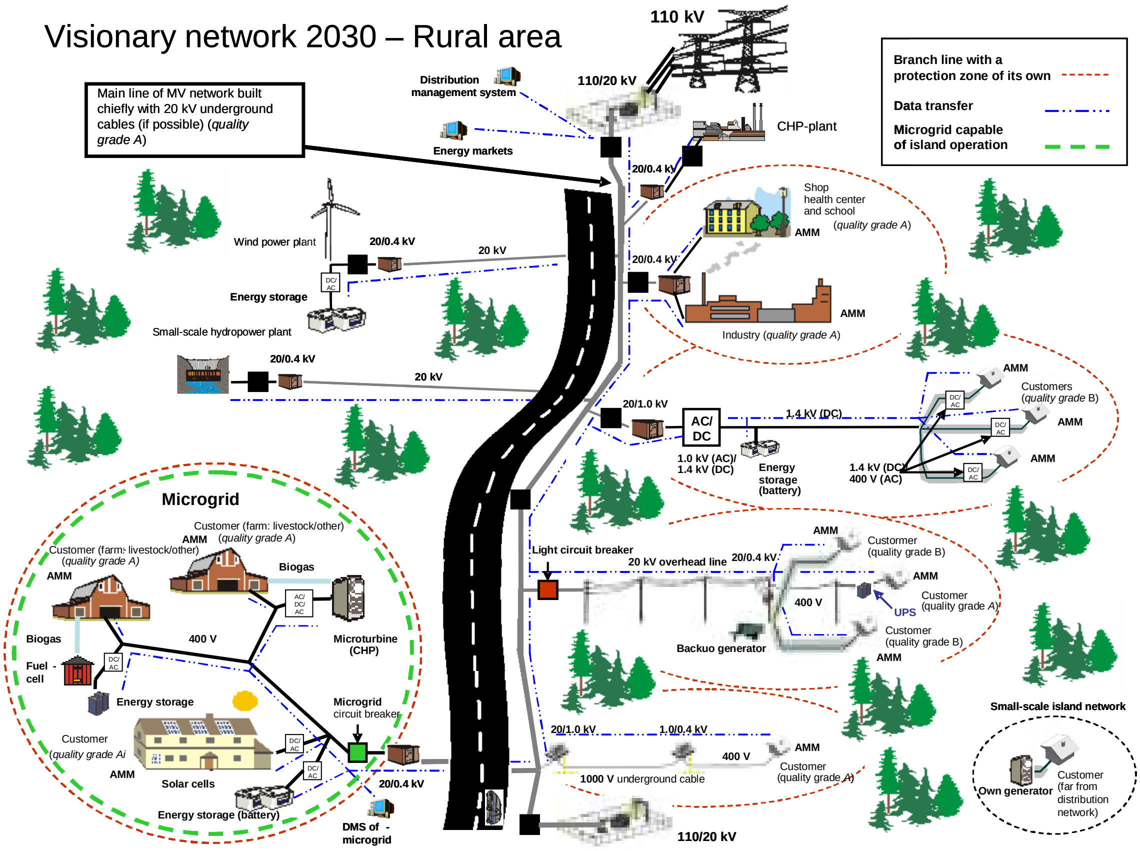

Figure 7.3. Visionary Network 2030 for rural area.

7.3 Visionary network for urban and regional networks

In urban and regional networks, the reliability issues are at least of equal importance as in rural networks, yet the scale of problems does not compare with that of overhead line networks in rural areas. Nevertheless, the reliability expectations have increased further, and answering these needs calls for constant development work. Reliability can be improved in near urban networks by increasing the degree of network automation. Within a longer time span, structural changes will improve reliability. In underground cable networks, network automation has not been considered economically feasible so far; however, an increase in outage costs and the overall technical and economic development of data communications technology will promote the development of cable network automation. In the city centres, the highest reliability expectations can be satisfied in the future by regional or customer-specific solutions, in which power electronics, distributed generation and energy storages play a key role.

So far, regional networks have been reliable, yet it is advisable to consider the risks of a possible fault occurring in an 110 kV branch line supplying several primary substations. This should be done in connection with designing redundancy for primary substations, provided from the medium-voltage side of the network.

A larger-scale renovation of urban networks lies ahead far later than in the case of rural networks; however, since for instance the life span of secondary components of primary substations is notably shorter than the life cycle of primary network components, it is already necessary to take the renovation strategies into consideration. On the other hand, there is not enough information on the remaining life time of the key primary network components, and therefore there is a need for the development of condition monitoring methods.

Both in the urban and regional networks, the load growth causes a need to reinforce the networks. Special features of these networks are an increase in the cooling load and the occurrence of a load peak in summer. The environmental effects of distribution networks, such as electric and magnetic fields and, in particular, issues associated with landscaping and land use have become central to network planning. For instance, a significant proportion of the construction costs of urban cable networks are structural costs, and therefore the development of structural solutions is of central importance. Cost efficiency can be improved by co-operation with other infrastructure construction. There is pressure for invisible infrastructure, that is, underground cabling of also the large-power transmission for cities.

Figure 7.4 presents a scheme for solutions in urban areas; the chart includes rationale for the solutions, based on the evaluation of changes in the operational environment and the present state of the networks.

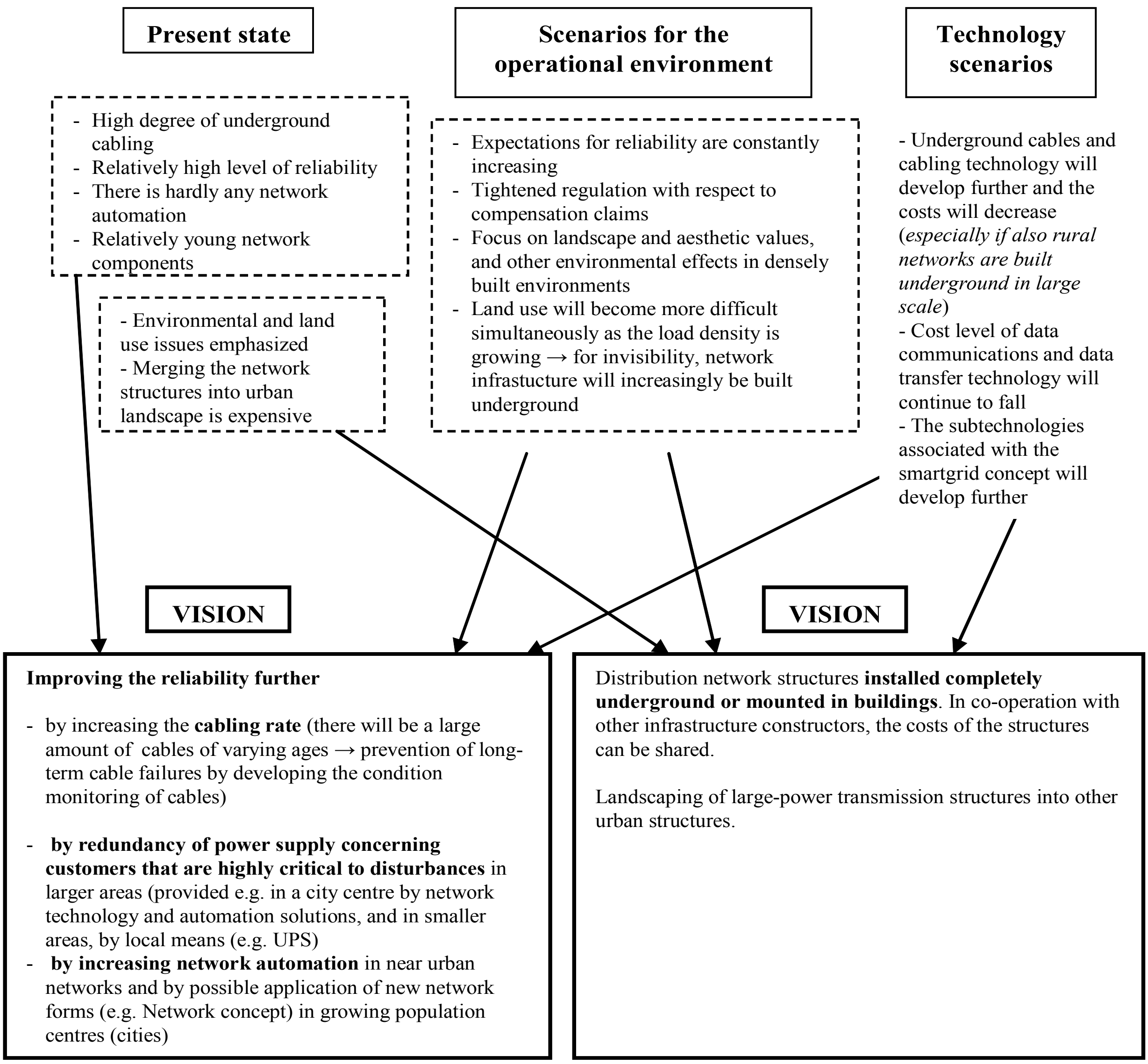

Figure 7.4. Improving the reliability of supply in urban areas and fitting the network structures into urban environment.

Further, the view proposed in Figure 7.2 of the opportunities of the distributed energy resources is applicable also to urban conditions.

7.4 Uncertainty factors associated with network development

In the future, there may be rapid changes in the factors impacting the development of distribution networks. Naturally, regulation, network ownership issues and owner policy are all of great significance. For the distribution network companies, there are certain external factors, the development of which has to be carefully followed up:

- Development of information and communications technology
- Technical and economic development of distributed generation, for instance fuel cells and bioenergy

- Development of materials technology and its effects on battery technology and thereby on hybrid cars, and the development of superconductive cables.
- New network components with power electronics; these can be considered as intelligent components
- Climate change and its associated long-term forecasts
- Environmental issues and associated requirements

8. Technology Roadmap for distribution networks

Among the objectives of the Distribution Network 2030 project was to investigate whether it is necessary to launch a Roadmap project to direct and coordinate the development in the field. During the Distribution Network 2030 project, it soon became obvious that there is a need for a further Roadmap project. It is probably most advantageous to implement the project in two stages; the first stage involves planning the Roadmap and delineating the project clusters, taking into account other on-going projects elsewhere in the world, such as the EU SmartGrids Technology Platform. In the second stage, the Roadmap will be implemented in concrete research and development projects. Figure 8.1 introduces a preliminary scheme for outlining the topic areas in the research.

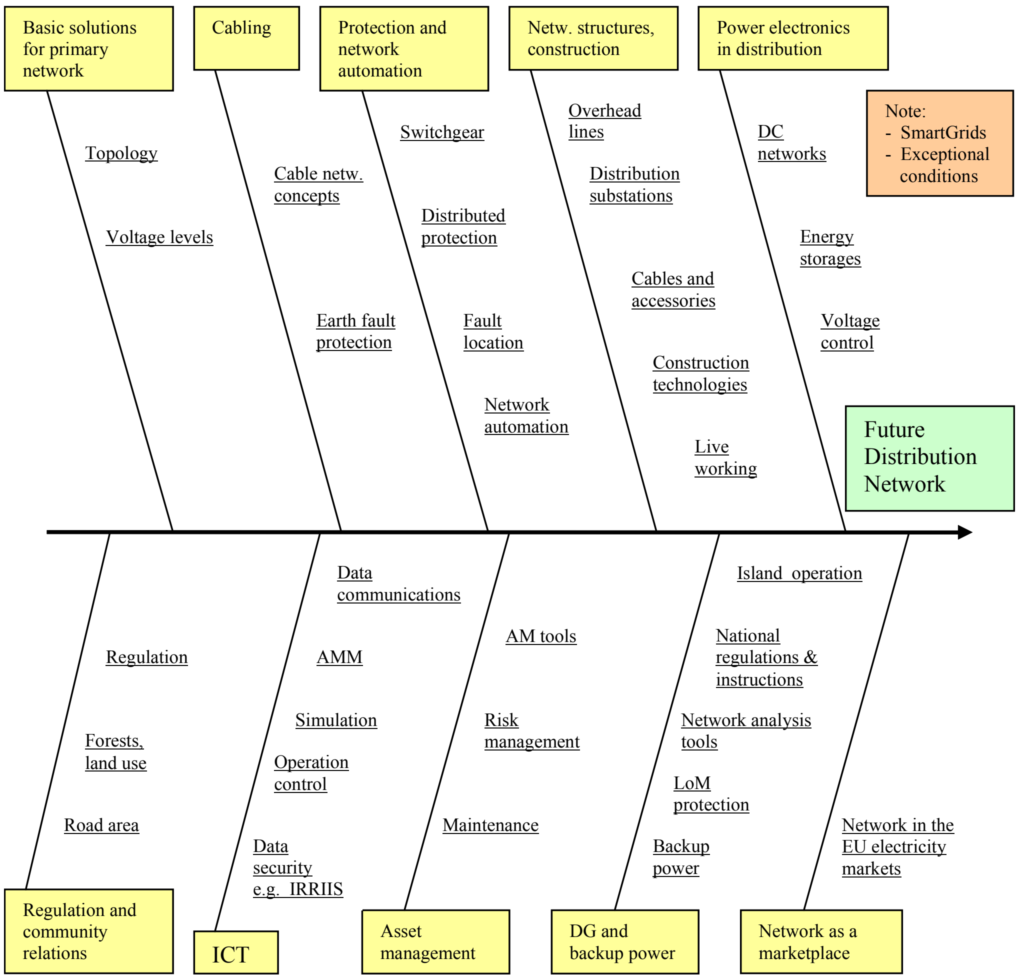

Figure 8.1. Preliminary scheme for Roadmap project planning.

The implementation of Roadmap calls for commitment to the project and both material and intellectual contributions from research institutes, distribution network companies and technology industry.

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Sähkönjakelutekniikkaan liittyvä tutkimustoiminta Suomessa
[Research activities in the field of electricity distribution technology.]
Tutkimuskartta_SUOMI.ppt

Sähkönjakelutekniikkaan liittyvä tutkimustoiminta muissa Pohjoismaissa
[Research activities in other Nordic countries associated with electricity distribution technology.]
Tutkimuskartta_POHJOISMAAT.ppt

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[Projects related to future network solutions in other countries.]
Muiden maiden tulevaisuuden verkkoratkaisut projekteja1.doc

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