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# VOLTAGE SAGS IN POWER DISTRIBUTION NETWORKS

Doctoral Dissertation

**Pirjo Heine**

Helsinki University of Technology
Department of Electrical and Communications Engineering
Power Systems and High Voltage Engineering

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**Pirjo Heine**

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Electrical and Communications Engineering for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 25th of November, 2005, at 12 noon.

Helsinki University of Technology
Department of Electrical and Communications Engineering
Power Systems and High Voltage Engineering

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ABSTRACT OF DOCTORAL DISSERTATION

Author Pirjo Heine

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Voltage sags in power distribution networks

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☒ Article dissertation (summary + original articles)

| | |
|---|---|
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| Laboratory | Power Systems and High Voltage Engineering |
| Field of research | Power Systems |
| Opponents | Professor Dr. Herwig Renner & Dr. Anssi Seppälä |
| Supervisor | Professor Matti Lehtonen |

Abstract

Voltage sags have become increasingly important when considering the various power quality issues that cause inconvenience to customers. For some customers voltage sags cause especially high costs. Thus, power distribution companies should understand the voltage sags experienced in their networks and their options in terms of decreasing the influence of voltage sags. In this thesis, voltage sag mitigation includes the use of conventional means and regular power system components.

This thesis introduces an extended method of fault positions to calculate the voltage sag distribution experienced in power distribution networks. The method uses only input data that is typically available and the basic fault calculations already in use in power distribution companies. The thesis also presents calculated and measured voltage sag distributions from Finnish power distribution networks. In addition, the thesis shows how various, specific power system characteristics affect the sag distribution. Sag-sensitive customers should be supplied by their own main transformers and the local distribution network kept as limited as possible. For overhead line networks, power distribution transformers should be protected against overvoltages using surge arresters instead of spark gaps. Underground cables are superior to overhead line networks, but mixed networks having both underground cables and overhead lines in the same distribution network should be avoided. Surprisingly, the increased level of distribution automation often gives rise to the most severe voltage sags. Since basic decisions in the development of power distribution networks may have a positive as well as negative influence on voltage sag characteristics, more awareness of these effects is needed.

In this thesis, the main focus has been voltage sags. However, voltage sags represent only one power quality issue to be taken into account in the planning and operation of power distribution networks. Thus, voltage sag analysis should not be a separate part of power distribution planning but should be included as one, important element in a comprehensive power system analysis. The economic calculations presented in this thesis showing the especially high costs caused by voltage sags strengthen this claim.

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# PREFACE

The research work related to this thesis has been carried out in the Power Systems and High Voltage Engineering Laboratory of the Helsinki University of Technology. In addition to the university, the TESLA technology programme by TEKES, the Graduate School in Electrical Engineering, the Sähköturvallisuuden Edistämiskeskus ry, and the Ulla Tuomisen säätiö have financially supported this project.

This work started under the guidance of Professor Erkki Lakervi. Later on Professor Matti Lehtonen took over the responsibility. I thank both of them for their support during this work. I especially thank Professor Matti Lehtonen for believing in my research during the many years and being the official supervisor of this thesis.

Professor Kimmo Kauhaniemi and Doctor Anssi Seppälä were the preliminary examiners of this thesis. I wish to express my sincere gratitude to them for reviewing my thesis.

This work has benefited greatly from the technical support of Kainuun Energia and especially Arvo Oikarinen. He was always ready to discuss and offer his skills when performing power quality measurements in the Kainuun Energia power distribution network. I have had several co-authors in the scientific papers. I wish to thank Erkki Antila and Jaakko Pitkänen for having had the possibility to apply your expertise to the research area of this thesis. Especially warm thanks are addressed to my colleague and one of the co-authors Pasi Pohjanheimo. We shared the same office for several years. I received support in questions related to voltage sags and other scientific issues, performing power quality measurements, and in computer problems. I highly appreciate your friendship in our power quality group.

The personnel of the Power Systems and High Voltage Engineering have offered a pleasant and encouraging working atmosphere. I have been privileged to know so many of you. John Millar deserves a special mention. In addition to his scientific work, he has managed in a positive way to correct and improve my English language over the last few years. He has checked the English language of this thesis and I want to thank him.

Finally, I would like to thank my loving family Jari, Sari, Riikka and Laura for having you in the dearest place in my heart.

In Espoo, September, 2005

Pirjo

## PUBLICATIONS

This thesis consists of the present summary and the following publications, referred to as Publications I-VIII.

I Heine, P., Lehtonen, M., Lakervi E., Voltage Sag Analysis Taken into Account in Distribution Network Design, 2001 IEEE Porto PowerTech'2001, Porto, Portugal, September 10-13, 2001, Volume III, Paper PSP-222, 6 p.

II Heine, P., Pohjanheimo, P., Lehtonen, M., Lakervi, E., A Method for Estimating the Frequency and Cost of Voltage Sags, IEEE Transactions on Power Systems, Vol. 17, No. 2, May 2002, pp. 290-296.

III Heine, P., Pitkänen, J., Lehtonen, M., Voltage Sag Characteristics of Covered Conductor Feeders, 38th International Universities Power Engineering Conference, UPEC 2003, Thessaloniki, Greece, September 1-3, 2003, 4 p.

IV Antila, E., Heine, P., Lehtonen, M., Economic Analysis of Implementing Novel Power Distribution Automation, CIGRE/IEEE PES International Symposium on Quality and Security of Electric Power Delivery Systems, Montreal, Canada, October 8-10, 2003, 6 p.

V Heine, P., Lehtonen, M., Voltage Sag Distributions Caused by Power System Faults, IEEE Transactions on Power Systems, Vol. 18, No. 4, November 2003, pp. 1367-1373.

VI Heine, P., Lehtonen, M., Oikarinen, A., Overvoltage Protection, Faults and Voltage Sags, 11th International Conference on Harmonics and Quality of Power, ICHQP 2004, Lake Placid, New York, USA, September 12-15, 2004, 6 p.

VII Heine, P., Turunen, J., Lehtonen, M., Oikarinen, A., Measured Faults during Lightning Storms, 2005 IEEE PowerTech'2005, St. Petersburg, Russia, June 27-30, 2005, 5 p.

VIII Heine, P., Lehtonen, M., Oikarinen A.: The reliability analysis of distribution systems with different overvoltage protection solutions, 15th Power Systems Computation Conference, PSCC 2005, Liege, Belgium, August 22-26, 2005, 7 p.

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PUBLICATIONS I – VIII

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| A | ampere |
| A, A(1,1) | matrix, element (1,1) of matrix A |
| $c_k$ | earth fault factor |
| d | transformer connection (delta) |
| Dyn | transformer connection |
| Dyn11 | transformer connection |
| € | euro |
| ft | fault type |
| EHV | Extra High Voltage |
| EN | European Norm |
| $F(u,t)_k$ | cumulative sag distribution |
| $f(U_{Sag})$ | sag distribution |
| $f_{pf}(U_{Sag})$ | sag distribution caused by permanent faults |
| HSAR | High-Speed Auto-Reclosing |
| HV | High Voltage |

| | |
|---|---|
| i | integer / imaginary unit |
| IEEE | The Institute of Electrical and Electronics Engineers |
| k | integer |
| $k_{2/3}$ | sag influence of a two-phase short circuit compared to a three-phase short circuit |
| km | kilometre |
| kV | kilovolt |
| kVA | kilovoltampere |
| LV | Low Voltage |
| m | metre |
| ms, msec | millisecond |
| MV | Medium Voltage |
| n | integer |
| NOP | Normal Open Point |
| $n_{hs}$ | number of faults cleared by high-speed autoreclosure |
| $n_{pf}$ | number of permanent faults |
| $n_{td}$ | number of faults cleared by time-delayed autoreclosure |

| | |
|---|---|
| P | transformation matrix |
| $P^{-1}$ | inverse of matrix P |
| $p_{i,ft}$ | shares of various fault types ft of fault position i |
| $p_{sc,hs}$ | share of short circuits in faults cleared by high-speed autoreclosure |
| $p_{sc,pf}$ | share of short circuits in permanent faults |
| $p_{sc,td}$ | share of short circuits in faults cleared by time-delayed autoreclosure |
| $p_{sc,3}$ | share of three-phase short circuits in all short circuits |
| PCC | Point of Common Coupling |
| r | integer |
| pu | per unit |
| rms | root mean square |
| s | second |
| SFS | Finnish Standards Association |
| t | time |
| $\Delta t_{i,ft}$ | sag duration for fault type ft and fault position i |
| u, U | voltage |

| | |
|---|---|
| $U_C$ | declared supply voltage |
| $U_s$ | prefault voltage of the busbar |
| $U_{sag,crit}$ | critical remaining voltage during a voltage sag |
| $u_k$ | voltage of node k |
| $U_{0,i}$, $U_{0,r}$ | prefault voltages of node i and r |
| $U_{pri}$ | voltage on the primary side of a transformer |
| UPS | Uninterruptible Power Supply |
| $U_{sag}$ | sagged voltage (remaining voltage during the sag) |
| $U_{sag,i}$ | sagged voltage of node i |
| $U_{sag,r}$ | sagged voltage of node r |
| $U_{sec}$ | voltage on the secondary side of a transformer |
| V | volt |
| XLPE | cross-linked polyethylene |
| Y, y | transformer connection (star) |
| YNyn | transformer connection |
| YNyn0d | transformer connection |
| YNd11 | transformer connection |

| | |
|---|---|
| $Z$ | impedance |
| $z_{ir}$ | transfer element of the node impedance matrix |
| $z_{rr}$ | diagonal element of the node impedance matrix |
| $Z_F$ | fault impedance |
| $Z_L$ | line impedance |
| $Z_S$ | source impedance |
| $Z_T$ | transformer impedance |
| $\alpha$ | angle |
| $\lambda_{i,ft}$ | fault frequency of fault type ft and fault position i |
| $\lambda_i$ | fault frequency of fault position i |
| $\Omega$ | ohm |

# 1 INTRODUCTION

The various factors that make up power quality have developed together in the course of time and in step with the overall development of society and the electrical industry. Interest in power quality has moved from long interruptions and undervoltage towards shorter-duration phenomena, such as shorter interruptions and voltage sags. Nowadays, for some special customers, the economic losses caused by voltage sags may even be higher than the costs associated with interruptions. Voltage sag analysis should thus be considered as one essential input in the technical and economic optimisation of distribution network design and operation. In this thesis, the main interest is the voltage sags experienced by customers connected to power distribution networks.

The increase in understanding obliges power distribution companies to provide their customers with more information regarding voltage sags. Power distribution companies should be aware of the characteristics of voltage sags experienced in their network. In addition, they should be able to evaluate the effect of alternative system configurations on voltage sags and their possibilities to reduce the inconvenience caused by sags.

An important part of this thesis is to introduce the voltage sag distribution, i.e., the expected number of voltage sags experienced by a customer during a year. A simplified model is developed and introduced for this calculation. In addition, examples of calculated and measured voltage sag distributions are presented. Voltage sag characteristics are expected to change if certain specified network improvements are carried out. In this thesis, typical power system characteristics are judged in terms of voltage sags.

This thesis introduces as main contributions:

- An extended method of fault positions to calculate the voltage sag distribution experienced by customers in power distribution networks.
- Examples of calculated and measured voltage sag distributions.
- Analysis of the influence of various network characteristics on experienced voltage sags. This part includes the analysis of network characteristics such as
  - overvoltage protection of power distribution transformers (spark gaps / surge arresters / externally gapped metal-oxide surge arresters)
  - medium voltage feeder type (bare overhead line / covered overhead line / underground cable / mixed feeder types)
  - power distribution automation (various levels of automation implemented in different network types).

As a result of this thesis the influence of certain power system characteristics on voltage sag characteristics can be evaluated. Accurate estimates of a sag distribution enable power distribution companies to serve sag-sensitive customers and also assure their own status among the several demands coming from their more demanding customers as well as the electricity authorities.

The thesis consists of a summary with six Chapters and the original papers, Publications I-VIII, which are enclosed as Appendices. Chapter 2 defines voltage sags and the causes of voltage sags. Chapter 3 introduces the calculation of a voltage sag distribution and the main aspects to be taken into account in the calculations. Chapter 4 applies the developed model and gives examples of calculated and measured voltage sag distributions. Chapter 5 is the main chapter of this thesis. It introduces how the overvoltage protection of power distribution transformers, different MV feeder types and distribution automation affect the sag distribution. The summary ends with Conclusions in Chapter 6.

The original papers, Publications I-VIII, are presented at the end of this thesis. The writer has been the main author of all the papers except Publication IV, in which, however, the writer herself performed all the modelling and calculation of voltage sags. These results were then used by the first author in question as an input in the economic calculations presented in the publication. The modelling and calculations in Publication II were performed, in equal part, by the first two authors.

# 2 VOLTAGE SAGS IN A POWER DISTRIBUTION NETWORK

## 2.1 Definition of voltage sag

The main properties characterizing voltage sags are the magnitude, the duration and the number of sags experienced during a year, the sag frequency. The European standard EN 50160 (1999) "Voltage characteristics of electricity supplied by public distribution systems" defines a voltage sag (dip) as "A *sudden reduction of the supply voltage to a value between 90% and 1% of the declared voltage* $U_C$, *followed by a voltage recovery after a short period of time. Conventionally the duration of a voltage dip is between 10 ms and 1 minute*". The IEEE Std 1159-1995 "IEEE recommended practice for monitoring electric power quality", limits the sag magnitude to between 0.1 pu and 0.9 pu and the duration to between 0.5 cycle and 1 minute (IEEE 1995). These standards do not specify the maximum allowed number of voltage sags.

Special attention should be paid when talking about the sag magnitude. The sag magnitude can have contrary meanings as it can be understood as the voltage drop (missing voltage) or the remaining (retained) voltage. In this thesis, the sag magnitude means the remaining voltage during the sag. Terms "*sag*" and "*dip*" characterize the same phenomenon and are used in a similar way. In this thesis, the term "*sag*" is preferred. Generally, adjectives like "*shallow*", "*severe*", and "*deep*" are used to characterize voltage sags. "*Shallow*" means sags whose remaining voltage is high. On the contrary, "*deep*" characterizes a voltage sag with a low remaining voltage, and "*severe*" a sag that has a low remaining voltage and/or long duration.

The phenomenon of a voltage sag is manifold while voltage sags often affect each phase of a three-phase system differently depending on the nature of the disturbance (symmetrical / asymmetrical), transformer connections, earthing, and equipment connections. As an example, Fig. 1 shows a recording of a voltage sag caused by an asymmetrical fault, a two-phase-to-ground short circuit, that occurred and was measured in an MV (medium voltage) network. In addition, the characteristics of an asymmetrical voltage sag typically change when it propagates to other voltage levels. As a matter of fact, it is impossible to characterize voltage sags without determining which voltage (phase-to-ground / phase-to-phase), which phase(s) and which voltage level (low voltage LV / medium voltage MV / high voltage HV / extra high voltage EHV) are of concern and interest.

In this thesis, the lowest phase-to-ground voltage experienced in the phase concerned in the LV system is used to characterize the sag magnitude. Further, the number of sags caused by a single event is counted according to how many of the three phase-to-ground voltages are sagged on the LV side. The characteristics of voltage sags (magnitude, duration and sag distribution) are explained in more detail in Chapter 3.

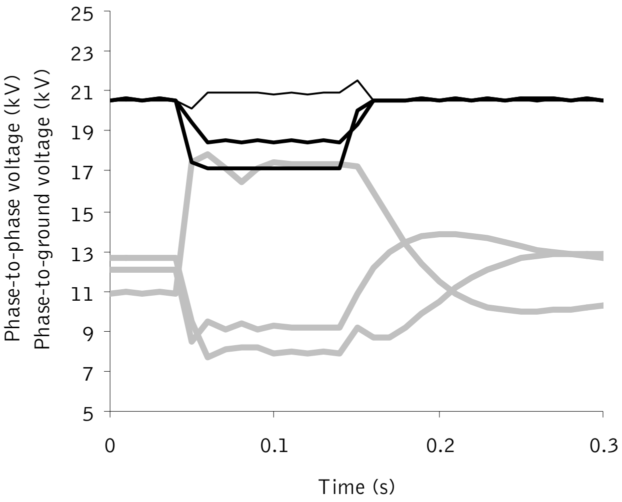

*Fig. 1. Sagged phase-to-phase (black) and phase-to-ground voltages (grey) measured in a 20 kV network having a compensated neutral. The sag was caused by a two-phase-to-ground fault in the MV network in question.*

## 2.2 Origin of voltage sags

Voltage sags typically appear in events having large currents flowing through the network impedances. Such events are, for example, power system faults, energizing of transformers, switching operations, starting of large motors and other large load changes in the power system (Bollen 1999).

A short circuit fault is a typical cause of a voltage sag. At the fault location, the voltages of the faulted phases are at their lowest. The sagged voltages rise as the distance from the fault place increases. The area affected by sags varies depending on the location of the fault and the network and fault characteristics. In principle, each LV customer may experience voltage sags caused by faults that occur in any part of the power system, (Fig. 2):

1. transmission (EHV) and subtransmission (HV) systems
2. local MV distribution system
3. neighbouring MV distribution systems
4. local LV distribution system
5. neighbouring LV distribution systems.

However, voltage sag propagation is to some extent inhibited and not all the power system areas presented in Fig. 2 have to be taken into account in sag analysis. Some power system parts have a major contribution to the experienced voltage sags, but not all power system parts are so critical in this sense. The question of which power system parts should be taken into account in voltage sag analysis should be addressed on each voltage level.

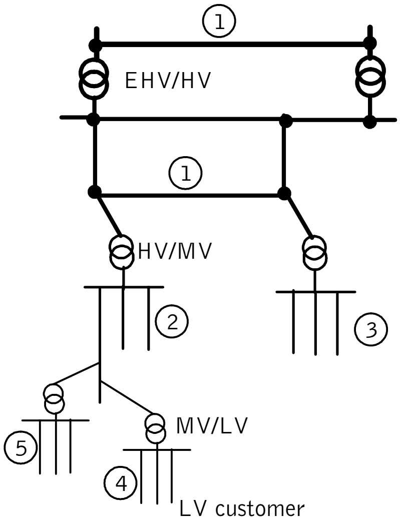

*Fig. 2. The origin of fault positions that may cause sags experienced by an LV customer (Publication V).*

Essential aspects to be taken into account are:

- The structure and the stiffness of various power system parts as well as the protection coordination affect the voltage sag propagation.
- Faults on certain power system areas (for example, EHV transmission systems, power systems comprising underground cables) are rare events. When there are no faults, there are no sags caused by faults.
- Transformer connections may prohibit asymmetrical sags to be experienced as sags at other voltage levels. On the other hand, symmetrical sags caused by a three-phase fault lead to severe sags on a large number of buses at various system levels. On the contrary, single-phase earth faults may be not at all or only slightly experienced at the adjacent voltage levels

Sagged voltages may also appear when energizing transformers. A typical example of this in an MV power distribution network is the closing of a circuit breaker at the HV/MV substation to energize an MV feeder. One MV feeder may supply dozens of power distribution transformers. When a circuit breaker is closed at the substation all the power distribution transformers supplied by the feeder in question are energized at the same time. High inrush currents are taken by the transformers and short-duration sagged voltages are experienced in the whole substation area. In overhead line MV networks, where autoreclosure sequences are used for protection purposes, this procedure takes place repeatedly when clearing a temporary fault. There may be events where the fault itself does not cause sagged voltages at the location of interest, but the repetitive opening and closing of a faulted MV feeder does. Fig. 3 presents an example.

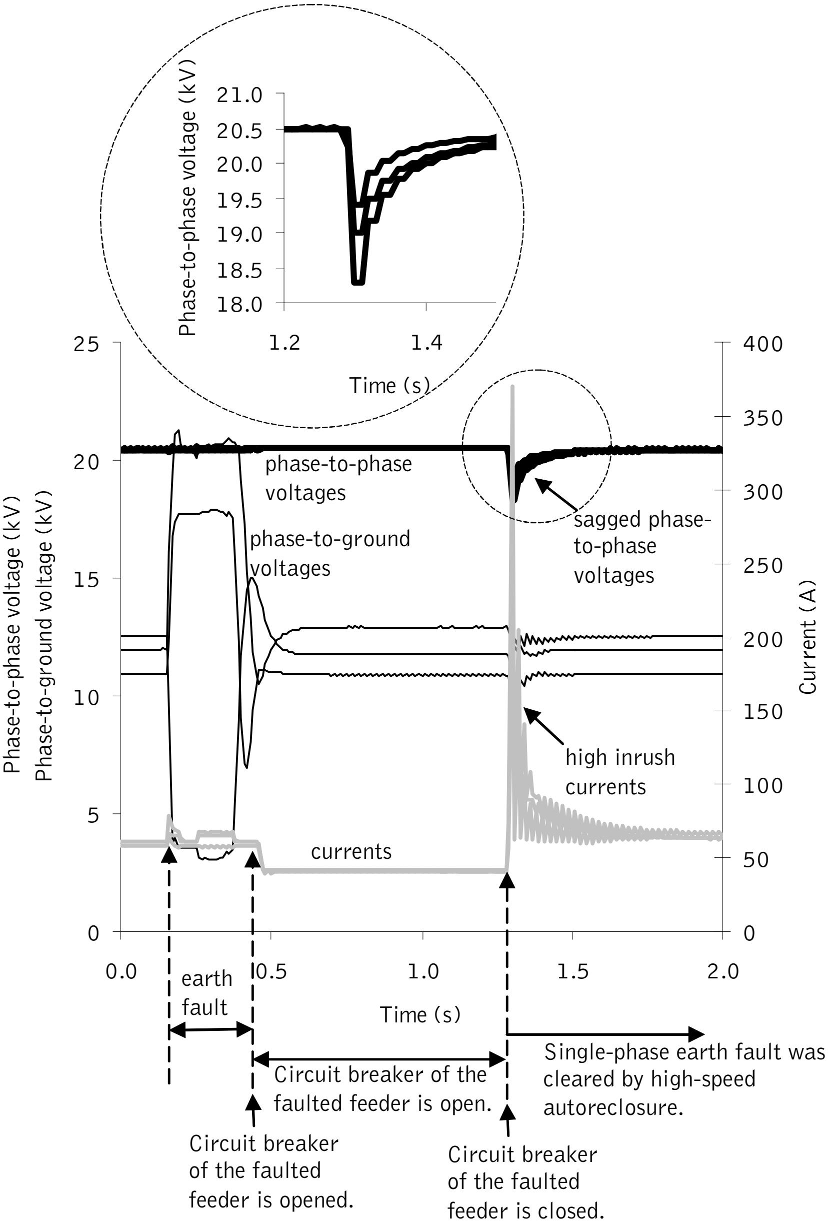

*Fig. 3. A single-phase earth fault and a forthcoming autoreclosure causing sagged phase-to-phase voltages. The single-phase earth fault causes no sagged phase-to-phase voltages but the closing of the circuit breaker and the consequent inrush currents do.*

In Fig. 3, a single-phase earth fault occurs in an MV network. With a Dyn connected MV/LV transformer the phase-to-phase voltages are of interest on the MV side. The single-phase earth fault causes no sagged phase-to-phase voltages on the MV side. A circuit breaker is opened to clear the fault. When the circuit breaker at the substation is again closed, high inrush currents taken by all the power distribution transformers (116 transformers in this case) cause a voltage sag with a magnitude of $U_{sag} = 89\%$ of the remaining voltage. The voltage sag is experienced in the whole substation area. Inrush currents of power distribution transformers may typically be 5-8 times the normal load current (Westinghouse 1964). The fault disappeared during the de-energized time and was thus cleared by high-speed autoreclosure. The fault itself caused no sagged phase-to-phase voltages, but the energizing of the transformers did.

High currents also exist when large induction motors are started. Various causes of voltage sags produce different voltage profiles: for example, for motor starting, there is typically a rather small voltage drop followed by a gradual recovery of all phases (Fig. 4). Because motors are usually placed at lower voltage levels, the affected area of these voltage sags is mainly local. In addition to the starting of motors, this concerns all the power system operations that occur at lower voltage levels (load changes, switching operations) as well.

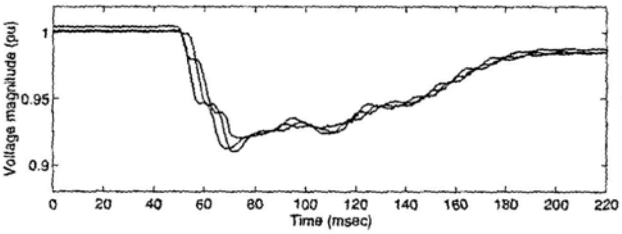

*Fig. 4. Voltage magnitude during induction motor starting (measured in a 400 V network) (Styvaktakis 2002).*

# 3 VOLTAGE SAG DISTRIBUTION

## 3.1 Definition of voltage sag distribution

A cumulative sag distribution is used to model voltage sags that are expected to be experienced at a certain location in the network during the observation period, typically one year. The cumulative sag distribution gives the number of voltage sags having equal or smaller remaining voltage than the threshold value and lasting a longer time than the duration of the threshold values indicates (Publication V):

$$F(u,t)_k = \sum_{i}^{n} \sum_{ft} (\lambda_{i,ft} \mid u_k \leq u, \Delta t_{i,ft} > t) \tag{1}$$

where $\lambda_{i,ft}$ is the fault frequency of fault type $ft$ at fault position $i$, $u_k$ the sagged voltage experienced at node $k$, and $\Delta t_{i,ft}$ the sag duration for the fault place and fault type in question.

The cumulative sag distribution gives the total number of voltage sags that are more severe than the critical threshold values indicate. The sag distribution can also be presented as a non-cumulative distribution. The non-cumulative distribution shows more clearly what sag characteristics the majority of voltage sags represent. As an example, Fig. 5a presents a non-cumulative sag distribution and Fig. 5b the respective cumulative one. The right front corner represents the most severe sags (low sag magnitude and long sag duration). These sag distributions have been measured in an MV network and the sags were caused by power system faults.

In general, the sag distribution includes all the sags caused by any reason that might occur at any location in the power system. In this thesis, the main focus is the sag distribution caused by power system faults and experienced by an LV customer. Thus, here the sag distribution includes all the sags caused by faults

- at any of the voltage levels in the network
- of any fault type
- of any fault clearing sequence.

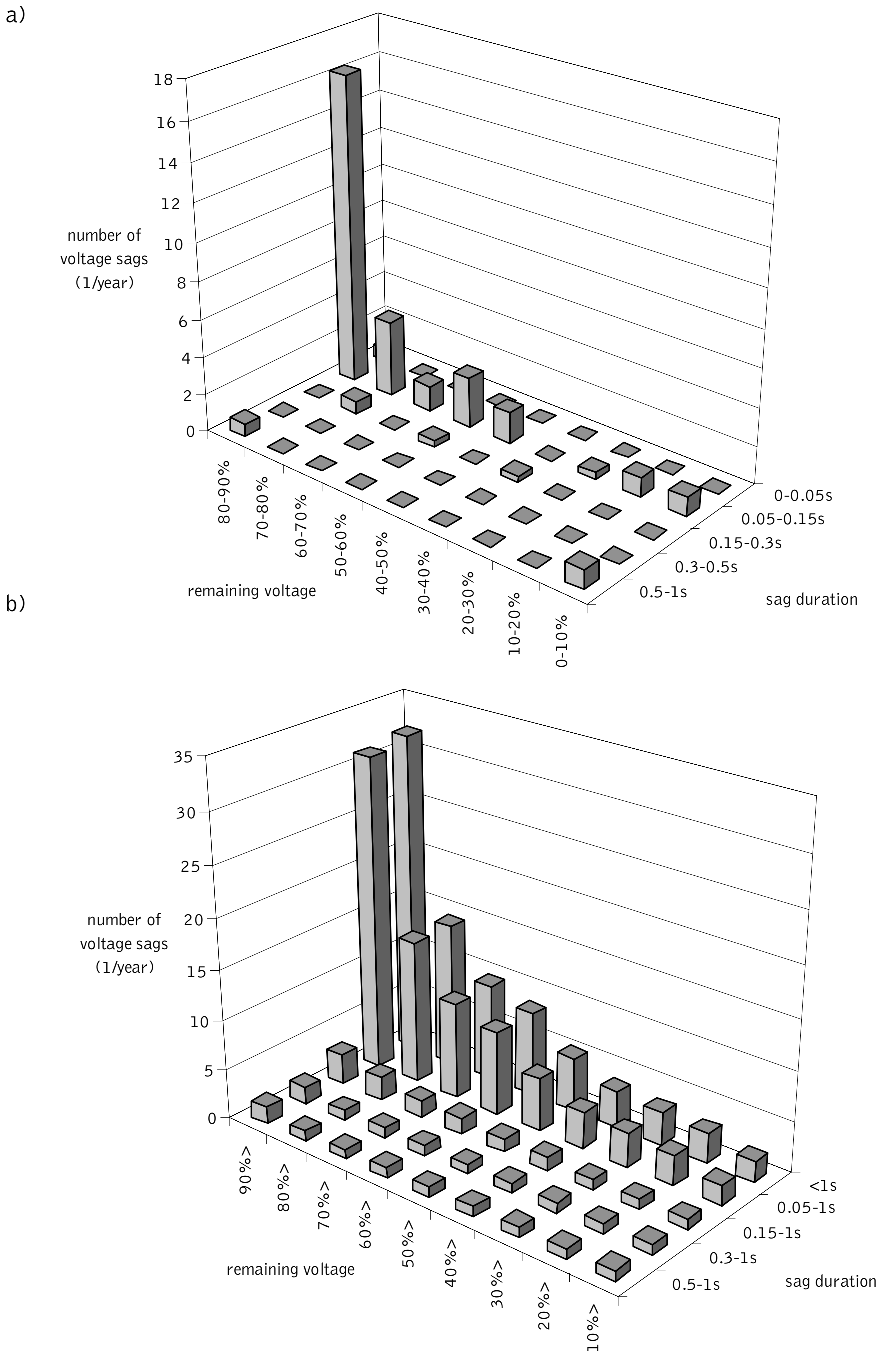

*Fig. 5. Annual sag distribution presented as a) a non-cumulative, b) a cumulative sag distribution.*

As already mentioned, the sag distribution is determined for a certain network point. Because each phase experiences a different sag distribution, the distribution could be calculated for each phase-to-ground and/or phase-to-phase voltage separately. The application or the purpose of use should determine the appropriate and the case-sensitive criteria for the calculations. In this thesis, only one sag distribution for each network point of interest is determined. For the sag magnitude the lowest phase-to-ground voltage experienced by an LV customer is used. Further, the number of sags caused by a single event is counted according to how many of the three phase-to-ground voltages are sagged on the LV side. Fig. 6 presents two voltage sags that can be characterized by the same magnitude and duration. However, a difference is made when determining the sag frequency. In Fig. 6a, all three phase-to-phase voltages sag, but in Fig. 6b, only one phase-to-phase voltage experiences a deeper sag. Standards do not determine how to calculate the sag frequency. While in Finland MV/LV transformers are delta/star connected, the phase-to-phase voltages on the MV side characterize the voltage sag magnitude. Thus, in Fig. 6a, the number of sags would be counted as *1 sag* and in Fig. 6b, *1/3 sag* (per phase). The way to determine the sag distribution on this basis involves a certain simplification.

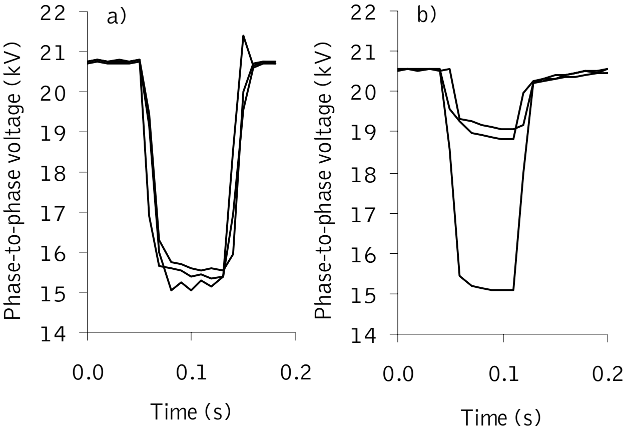

*Fig. 6. Sagged phase-to-phase voltages measured in a 20 kV network. The sag was caused by a) a three-phase fault, b) a two-phase fault.*

## 3.2 Calculation of voltage sag distribution

### 3.2.1 Stochastic methods

Generally, in stochastic prediction methods, modelling techniques are used to determine the expected values, standard deviation, etc., of a stochastic variable. A model and data representing the model are needed. When applying stochastic methods to voltage sag calculations, the response of the power system to generated faults is combined with the reliability data of the power system. The applied model represents the power system with a given set of parameters, such as, data of the network components, the network configuration and behaviour, and protection parameters. The accuracy of the power system model can be developed, tested and improved, and more detailed results can be achieved. However, one of the major challenges in voltage sag calculations is in determining the detailed reliability data of the power system.

Generally, in voltage sag calculations, either the method of fault positions or the method of critical distances is used (IEEE 1998, Bollen 1996). In the method of fault positions, a number of faults with different characteristics are generated throughout the power system and the voltage sag characteristics (magnitude, duration) are calculated and determined in the network point of interest. Each fault position should represent the location of a fault leading to sags with a corresponding magnitude and duration at the point of interest. Reliability data representing the fault frequency of each fault position is linked to the corresponding calculation results of the voltage sag characteristics. This procedure is repeated many times for different fault locations and fault types to determine the voltage sag distribution.

The other stochastic method in voltage sag calculations is the method of critical distances. While the method of fault positions is used to calculate the voltage sag characteristics for a given fault position, this method calculates the fault position for a given voltage. A fault closer to the network point of interest would cause a deeper sag. This method is typically used, not to calculate the sag distribution, but for case-sensitive calculations to determine the expected number of equipment trips at a certain network location.

In this thesis, the method of fault positions is applied. The method predicts long-term mean values for voltage sag distributions. The principles of the method are then introduced. Faults are generated one by one at each fault position and

- the voltage sag characteristics (magnitude and duration) are determined for the voltage level of the fault event (Chapter 3.2.2)
- the voltage sag propagation throughout the power system to the network point of interest is taken into account (Chapter 3.2.3)
- the fault frequencies linked to each fault position are determined (Chapter 3.2.4)
- the nature of repetitive sags belonging to one fault event is determined (Chapter 3.2.5)

However, not all power system areas have to be included in the sag analysis. This will be discussed in Chapter 3.2.6. The principles listed above are also handled in Publication V.

### 3.2.2 Voltage sag magnitude and duration

When applying the method of fault positions various faults are generated all over the network, during which fault voltages and fault durations are determined for each case. To calculate voltage sag magnitudes caused by a symmetrical fault type, i.e., a three-phase short circuit, single-phase modelling can be used. In meshed transmission and subtransmission systems, the calculation of voltages is based on Thevenin's theorem and the network impedance matrix (Nagrath and Kothari 1989). To calculate the sagged voltage at bus *i* caused by a fault at node *r*, (2a) or (2b) can be applied

$$\underline{U}_{sag,i} = \underline{U}_{0,i} - \frac{\underline{z}_{ir}}{\underline{z}_{rr} + \underline{Z}_F}\underline{U}_{0,r} \tag{2a}$$

$$\underline{U}_{sag,i} = \underline{U}_{0,i} - \frac{\underline{z}_{ir}}{\underline{z}_{rr}}(\underline{U}_{0,r} - \underline{U}_{sag,r}) \tag{2b}$$

where $\underline{U}_{sag,i}$ and $\underline{U}_{sag,r}$ are the sagged voltages during the fault at nodes *i* and *r* respectively. $\underline{U}_{0,i}$ and $\underline{U}_{0,r}$ are the pre-fault voltages. $\underline{z}_{rr}$ is the driving element that corresponds to the diagonal element of the node impedance matrix, $\underline{z}_{ir}$ the transfer element of the node impedance matrix that corresponds to nodes *i* and *r*, and $\underline{Z}_F$ the fault impedance. Matrix $\underline{Z}$, which contains elements $\underline{z}_{ir}$ and $\underline{z}_{rr}$ is a full matrix. This means that a fault in any of the buses of the meshed transmission system would lead to a sagged voltage at the network point of interest. Less influence will be noticed, however, the farther the fault occurs from the network point of interest.

In radially operated networks, the calculation can be simplified. The voltage sag at the substation busbar can be calculated using the impedance divider principle (Bollen 1996). The sagged voltage of the substation busbar $\underline{U}_{sag}$ is seen in the whole substation area supplied by this busbar. Thus, the substation busbar represents the point of common coupling (PCC) for the faults in the network in question and experienced by the customers downstream (Fig. 7). The ratio of the impedances from the MV busbar to the fault and the total impedance of the fault current path gives the per unit value of the source voltage that remains at the busbar during the sag (3). The fault side impedance includes the impedances of the MV feeder ($\underline{Z}_L$) and the possible fault impedance ($\underline{Z}_F$), and the source side impedance includes the impedances of the supplying transmission system ($\underline{Z}_S$) and the main 110/20 kV transformer ($\underline{Z}_T$). A typical assumption is that the fault impedance has a value of 0 **Ω**.

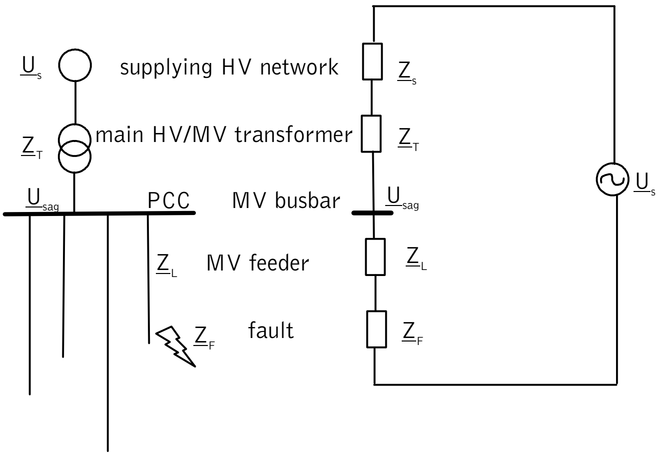

*Fig. 7. A circuit model for the voltage sag calculation in a radially operated MV network.*

$$\underline{U}_{sag} = \frac{\underline{Z}_L + \underline{Z}_F}{\underline{Z}_S + \underline{Z}_T + \underline{Z}_L + \underline{Z}_F} \underline{U}_S \tag{3}$$

where $\underline{U}_S$ is the voltage before the fault.

In three-phase short circuits, all three phase-to-ground and phase-to-phase voltages sag to the same degree. In asymmetrical faults, depending on the fault type, one, two or three phase-to-ground and phase-to-phase voltages are sagged, raised or remain unchanged. Calculations with symmetrical components must be applied (Grainger and Stevenson 1994). The sequence networks are connected differently in each fault type:

- In three-phase short circuits, only positive sequence values are applied.
- In two-phase short circuits, positive and negative sequence networks are connected in parallel.
- In two-phase-to-ground short circuits, positive, negative and zero sequence networks are connected in parallel.
- In single-phase earth faults, positive, negative and zero sequence networks are connected in series.

When considering voltage sags caused by power system faults, the sag duration is determined by fault clearing times. Generally, the more severe the fault, the more quickly the protection operates to clear the fault. With high fault currents, the shortest possible fault clearing time is used (instant tripping of a circuit breaker). These faults mean severe sags with low remaining voltages. With lower fault currents, an additional delay in the protection is allowed which also means longer sag duration. While in transmission systems fault currents are high, instant tripping is typically used. Thus, voltage sags caused by transmission faults usually have a short sag duration.

### 3.2.3 Voltage sag propagation

Voltage sags are transferred from one voltage level to another. When determining the sag distribution for a certain LV customer point, the sag magnitude and the sag duration are first determined at the voltage level of the fault event. The earthing practices and transformer connections then determine the sag propagation throughout the power system to the LV customer point. Again, sags caused by symmetrical three-phase short circuits transfer from one voltage level to another without changes, but for asymmetrical sags the voltages are propagated through transformers according to the equations (4)-(7) (Publication V).

$$\underline{U}_{\sec} = \underline{P}\underline{A}\underline{P}^{-1}\underline{U}_{pri} \tag{4}$$

$$P = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & \underline{a} & \underline{a}^2 \end{bmatrix} \tag{5}$$

$$\underline{a} = -0.5 + i\sqrt{3}/2 \tag{6}$$

$$A = \begin{bmatrix} \underline{A}(1,1) & 0 & 0 \\ 0 & 1\angle\alpha & 0 \\ 0 & 0 & 1\angle-\alpha \end{bmatrix} \tag{7}$$

In (4), matrix $P^{-1}$ transforms the phase-to-ground voltages to symmetrical components, while matrix $P$ does the opposite. Matrix A determines the transformer type. The element $A(1,1)$ depends on how the zero sequence component propagates through the transformer. If the zero sequence current cannot penetrate both windings then $A(1,1)$ is set to zero. In a YNyn transformer with both neutrals earthed, $A(1,1)=1$. Angle $\alpha$ is determined by the change in the positive sequence voltage. For example, for a Ynd11 type transformer, $\alpha=30°$.

### 3.2.4 Fault frequencies

One of the most challenging tasks in applying the method of fault positions is determining the detailed fault frequency of different power system parts. Not only the total fault frequency should be known, but also the shares of different fault types. This is because different fault types cause different voltage sag characteristics. Knowing the fault frequencies of certain network components would be insufficient. More detailed data is needed about what fault type is caused by the failure of a certain component or due to a certain cause of a fault.

Fault locations and fault types may vary with time depending on geographical locations and weather conditions. Fault locations and types may not be uniformly distributed as there may be sections of lines or buses exposed to adverse environmental conditions, causing greater fault occurrence probabilities or major fault types. By using individual fault characteristics for each line or non-uniform fault distribution, calculated sag distributions may coincide better with reality than using average, constant fault frequency values for the whole network.

The problem is the lack of real, long-term detailed fault data from different power system areas. At this stage, power quality measurements could answer this question. However, power quality measurements have their disadvantages, such as the long time needed for adequate precision and the questions of how to extrapolate certain results from one network to another network or to another time.

In sag calculations, the total fault frequency $\lambda_i$ of each power system part must be divided according to the type of fault: single-phase, two-phase, and three-phase faults, with and without earth connections, in order to reflect the probability of occurrence for each fault type (Publication V)

$$\lambda_i = \sum_{ft} \lambda_{i,ft} = \sum_{ft} \frac{p_{i,ft}}{100} \lambda_i \tag{8}$$

The shares of the various fault types $p_{i,ft}$ will satisfy two properties, (9) and (10)

$$0 \le p_{i,ft} \le 100\% \tag{9}$$

$$\sum_{ft} p_{i,ft} = 100\% \tag{10}$$

### 3.2.5 Repetitive sags caused by one fault

Especially in overhead line areas, the majority of faults are self-clearing or transient in nature and autoreclosure sequences have been developed for the automatic clearing of these faults. In MV systems, the automatic sequence typically includes 2-4 trippings of a circuit breaker. If, after the autoreclosures, the fault has not disappeared, the trial switchings that are part of the manually operated fault location and isolating procedure might increase the trippings of a circuit breaker up to 5-10. Short interruptions are experienced in the faulted feeder but sagged voltages are experienced on the neighbouring feeders (Fig. 8). Different opinions exist as to how these repetitive sagged voltages should be handled when forming the sag distributions. If one permanent fault causes, for example, 10 repetitive sagged voltages, should the number of voltage sags then be 1 or 10 or something in between? In this thesis, it is assumed in a quite conservative way that one fault clearing procedure means one voltage sag to be included in the sag distribution. It is assumed that if customer equipment is just once disturbed during the repetitive sequence because of sagged voltages, the recovery of the equipment or process to normal working status would not be possible before the next sagged voltages in the same sequence appear. In purely underground cable feeders, autoreclosure is not in use since all faults are permanent.

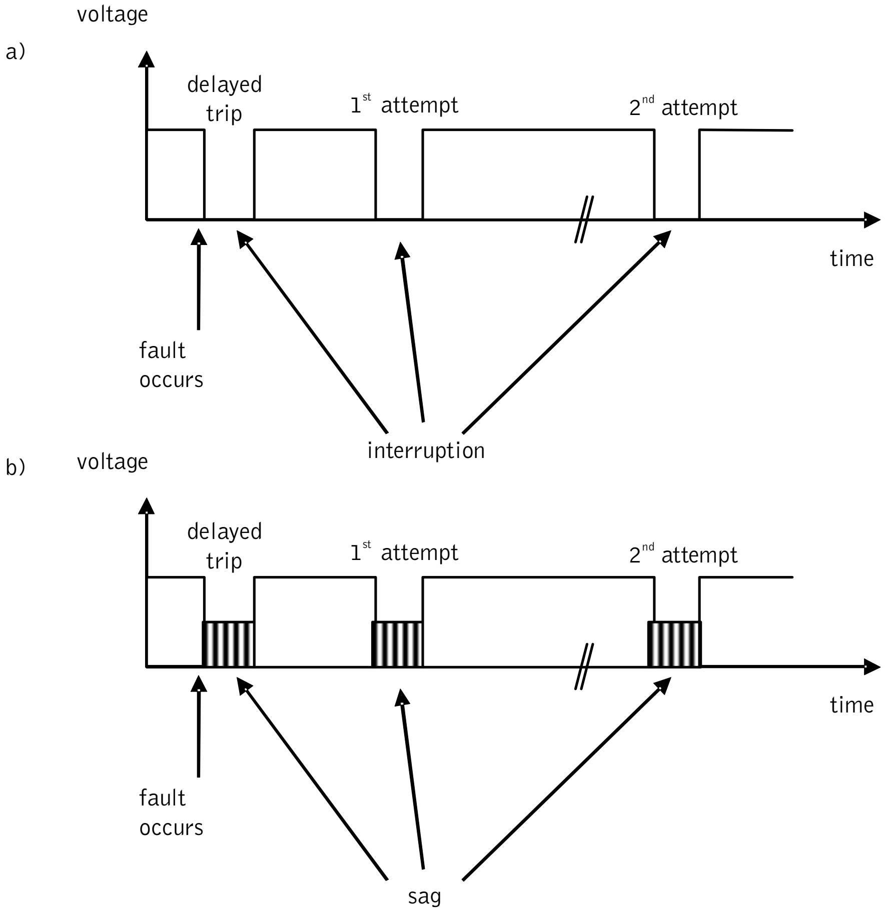

*Fig. 8. Voltages on a) a faulted feeder (Pohjanheimo and Lakervi 1999), b) a sound feeder, during autoreclosing attempts.*

### 3.2.6 Power system areas of major contribution

In principle, faults occurring anywhere in the power system may cause sagged voltages to be experienced at any location in the system. In voltage sag calculations, this would necessitate the modelling of the entire power system, from the highest voltage levels, possibly including thousands of kilometres of lines, down to the lowest voltage levels far and near. However, not all power system parts contribute to the sag distribution to the same extent. By taking into account the stiffness of different power system areas, the protection coordination, fault frequencies and the fault type propagation, the analysis of the sag distribution can be considerably limited.

In general, the meshed structure of a power system contributes to a wide sag propagation. Thus, transmission systems with a highly meshed topology supplying large geographical areas are vulnerable to wide sag propagation. Three-phase short circuits are severe faults. In a transmission system, such a fault would cause severe sags over a considerably large area, also including the distribution systems. Fortunately, three-phase short circuits are rare events in transmission systems.

While short circuit faults at higher voltage levels are to a large extent transferred to lower voltage levels, events causing sagged voltages at lower voltage levels have only little effect on higher voltage levels. This concerns, for example, the neighbouring MV and LV systems. Faults occurring in the neighbouring distribution systems are hardly experienced at higher voltage levels or further afield in the adjacent distribution systems.

When considering the various power system areas presented in Fig. 2, the most important areas to be included in sag analysis are the local MV system and the feeding HV subtransmission system. On the other hand, faults in the EHV transmission and local LV systems are typically very rare, and thus do not greatly contribute to the sag distribution. In addition, faults in neighbouring MV and LV systems are felt only slightly, if at all, in adjacent distribution systems.

# 4 CALCULATED AND MEASURED SAG DISTRIBUTIONS

Voltage sag distributions can be determined as equally well by computational network analysis as by measurements. However, when power system events causing voltage sags are randomly timed and randomly located the aim to achieve statistically reliable results from power quality measurements would require a painfully long measurement period. In addition, it is difficult to conclude from one measurement result at one location in a certain time period the sag distribution at another network location during another time period. Thus, the modelling of the network and the calculation of the voltage sag distribution are important tools in achieving the understanding of the network behaviour in the sense of voltage sags. Power quality measurements and calculations may complement each other in this matter.

In this thesis, the method of fault positions has been applied for voltage sag calculations using long-term average fault rates, average mixed fault types and fault clearing sequences. Thus, as a result the method predicts long-term mean values and not the particular performance during a given year. However, the application of this method is sufficient for the purpose of this thesis when the method is later used in Chapter 5 to research the relative changes in voltage sag distributions caused by modifications in network characteristics. Calculations could be compared with the measured results, but typically adjustment and judgment are needed when comparing measurements from a single year with calculations performed with long-term reliability values (Sikes 2000). Measurement projects have been performed worldwide, for example Koval and Hughes (1997), Sabin et al. (1999), Sikes (2000) and Kjϕlle et al. (2003).

## 4.1 Finnish power system

In this thesis, the Finnish power system (Fig. 9) is used as an example in the calculation and measurement of voltage sag distributions. Transmission systems (400 kV, 220 kV, 110 kV) are mesh operated and distribution systems (MV, 20 kV and LV, 0.4 kV) radially. Transmission systems are constructed mainly with overhead lines, in the biggest cities partly with underground cables. Typically, in rural areas, MV and LV systems have only overhead lines and in cities underground cables.

Power system characteristics vary in different parts of the country. In southern Finland, the stiffness of the power system is generally higher than in other parts. In rural areas, HV/MV substations supply lines dozens of kilometres long while, on the contrary, city areas are supplied by underground cables of considerably shorter feeder lengths.

Fault frequency affects the sag frequency. The fault frequency of transmission systems is low (Pottonen 2005). In Finland, the fault frequency of the 400 kV system is typically about one decade smaller than the fault frequency of the 110 kV system (Table 1). In overhead line MV systems, the fault frequency of permanent MV faults is typically in the order of 4-8 faults / 100 km / year (Sener 2003, Sener 2004). However, in overhead line areas where autoreclosure is in use, permanent faults only represent about 10% of all faults (Sener 2003, Sener 2004). In overhead line areas, the majority of faults are caused by weather related events, such as lightning, strong wind, falling trees, snow, etc. In MV networks having underground cables only, autoreclosures are not applied and all faults are considered permanent. In underground cable networks, excavation, misuse, mistakes in installation and planning, malpractice, overload or construction failure may cause permanent faults.

*Table 1. Fault frequencies and shares of different fault types for Finnish transmission systems (Elovaara and Laiho 1988).*

| Voltage (kV) | Fault frequency (faults per year per 100 km) | Shares of different fault types | | | |
|---|---|---|---|---|---|
| | | 1-phase earth faults | 2-phase short circuits | 3-phase short circuits | 2- or 3-phase earth faults |
| 400 | 0.28 | 80% | 2% | 3% | 15% |
| 220 | 0.72 | 78% | 2% | 3% | 17% |
| 110 | 3.5 | 81% | 3% | 2% | 14% |

Fig. 9 also presents the typical transformer connections and earthing practices. The earth fault factor $c_k$ describes the maximum phase-to-ground voltage in sound phases during a single-phase earth fault compared to the rated phase-to-ground voltage. LV systems are solidly earthed for safety reasons and MV systems are unearthed or have a compensated neutral. The neutrals of the 110 kV system are either unearthed or earthed with an impedance, $c_k$=1.7. Correspondingly, the 400 kV system has neutrals that are either impedance earthed or solidly earthed, $c_k$=1.4. Because of the Dyn11 connection in MV/LV transformers, the phase-to-phase voltages on the MV side are seen as phase-to-ground voltages on the LV side. The propagation of the neutral voltage from the HV or MV systems to the LV systems is not possible because of the delta connection in the MV system. Typically, about 80% of EHV, HV and MV faults are single-phase earth faults. Single-phase earth faults that occur in the 20 kV system are not seen as voltage sags on the LV side and faults that occur in the 110 kV network are only slightly felt (Publication V). Publications I and V introduce more detailed network characteristics of the Finnish power system in the sense of voltage sags.

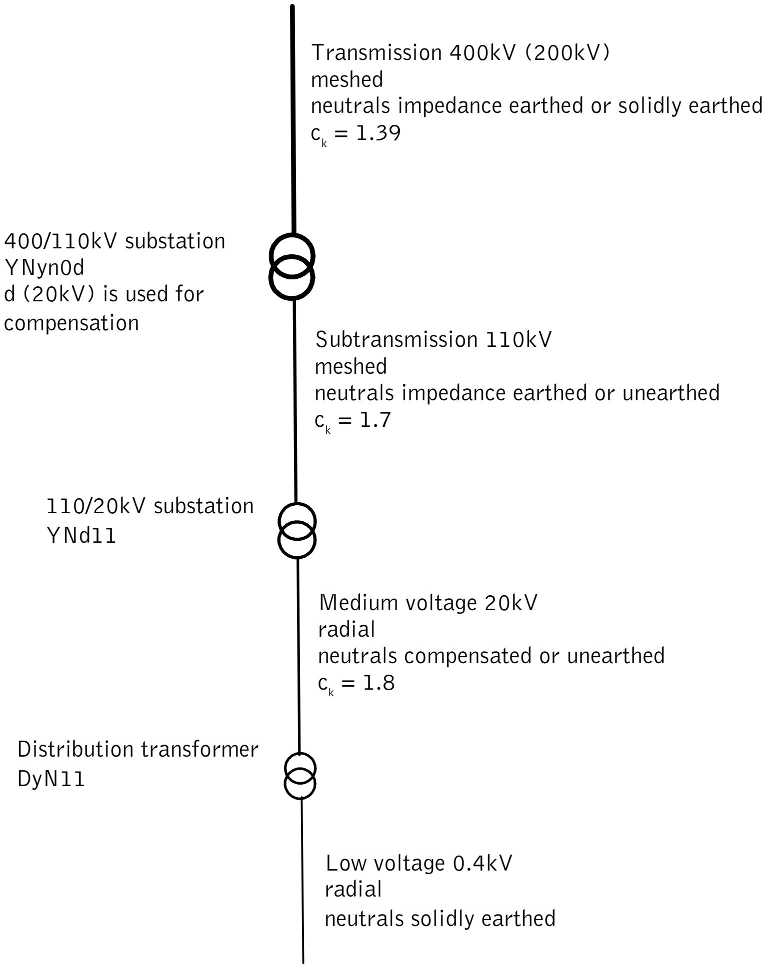

*Fig. 9. The principal structure of the Finnish power system. $c_k$ is the earth fault factor (the ratio between the maximum phase-to-ground voltage of the sound phase during a single-phase earth fault and the nominal phase-to-ground voltage).*

## 4.2 Calculated voltage sag distributions

### 4.2.1 Single-phase model

Power distribution companies usually administer mainly MV and LV networks and have a supply point from the transmission network. While faults in MV networks are typically a significant origin of voltage sags their influence on voltage sag distributions can not be neglected. Thus, there is a definite need for a calculation tool that can determine the voltage sags caused by MV faults. In addition, voltage sag calculations should be able to be performed using input data that is readily available.

The network data is no problem when power distribution companies have detailed technical data of their distribution networks. However, the availability of detailed fault frequency data is a challenge in voltage sag analysis. Traditionally power distribution companies only have data from permanent MV faults without knowing the shares of different fault types or the shares of temporary faults.

As a response to this inexactitude, Publication II presents an extension to the method of fault positions to determine the sag influence of faults in an unearthed MV network to the LV customers. The method of fault positions is applied using a single line model of the MV network and by generating only three-phase short circuits assuming the fault frequency of permanent faults. As a result a sag distribution $f_{pf}(U_{Sag})$ is obtained. This sag distribution is then modified according to the special characteristics of the network in question, using the following data

1. shares of different fault clearing sequences;
   a. ratio of faults cleared by time-delayed autoreclosure to permanent faults; $n_{td}/n_{pf}$
   b. ratio of faults cleared by high-speed autoreclosure to permanent faults; $n_{hs}/n_{pf}$
2. share of short circuits in every fault clearing sequence, such as;
   a. in permanent faults, $p_{sc,pf}$
   b. in faults cleared by time-delayed autoreclosure, $p_{sc,td}$
   c. in faults cleared by high-speed autoreclosure, $p_{sc,hs}$
3. share of three-phase short circuits in all short circuits faults, $p_{sc,3}$.

The introduced model can be written:

$$f(U_{sag}) = f_{pf}(U_{sag}) * (p_{sc,pf} + \frac{n_{td}}{n_{pf}} * p_{sc,td} + \frac{n_{hs}}{n_{pf}} * p_{sc,hs}) * (p_{sc,3} + (1 - p_{sc,3}) * k_{2/3}) \tag{11}$$

where $f(U_{Sag})$ is the voltage sag distribution (magnitude and number) experienced by all the customers. The factor $k_{2/3}$ is the sag influence of a two-phase short circuit fault compared to a three-phase short circuit fault. In this model, no additional factor incorporating the possible effect of sequential voltage sags has been used. This model can be applied to overhead line areas that use autoreclosure as well as to underground cable areas that do not have any automatic fault clearing.

In the model, single-phase earth faults can be ignored because single-phase earth faults on the MV side are not seen as voltage sags at LV customer locations. Short circuits are weighted according to how many of the phase-to-ground voltages on the LV side the fault type affects. Three-phase short circuits are seen in all phase-to-ground voltages similarly and they are weighted by a factor of *1*. In two-phase short circuits on the MV side, only one phase-to-phase voltage on the MV side is strongly disturbed and the two others only slightly. Thus in the model, two-phase short circuits are weighted by *1/3* ($k_{2/3} = 1/3$).

Publication V extends the use of the model to sags caused by HV faults and experienced by an LV customer. Again, single-phase earth faults are ignored and three-phase short circuits are taken into account by a factor of *1*. Single-phase earth faults that occur on the HV side are only felt slightly on the LV side. When the critical sag magnitude is not typically $U_{sag,\ crit} > 80\%$, neglecting the effect of single-phase earth faults in the HV system is justified. Two-phase short circuits are now taken into account by a factor of $k_{2/3} = 2/3$. This assumption exaggerates the sag influence of the most severe sags.

### 4.2.2 Results of calculations

Publication V presents calculated voltage sag distributions for four different cases representing strong and weak transmission areas and urban and rural distribution systems. It was found that not all power system areas have to be taken into account when forming the sag distributions. The most important areas are the MV system supplying the customer concerned and the 110 kV system. The neighbouring MV systems were also taken into account in the calculations. The primary reason not to include 400 kV and 0.4 kV systems in the sag analysis was because of their low fault frequency and the small length of affected feeder that is connected to one distribution transformer (0.4 kV). Fig. 10 shows the calculated cumulative sag distributions classified according to the fault origin, i.e., 110 kV system, the adjacent MV system and the local MV system.

The sag distributions were calculated applying the extended model of fault positions using long-term average fault rates, a mix of fault types and fault clearing sequences. The main results of the calculations were:

- Because of the construction of the meshed transmission system, sags caused by transmission faults propagate over long distances and affect the connected distribution areas, both urban and rural.
- Especially in rural systems that typically have long MV overhead line feeders and autoreclosure in use, MV faults represent the main cause of sags. The sag distribution mainly consists of sags caused by faults in the neighbouring MV feeders. In the case of a weak transmission system, the faults behind the neighbouring substation may also be of significance (Fig. 10). The sag frequency of the shallowest sags can be unpredictably high, especially in rural areas.
- In urban city areas, transmission faults may act as an important cause of sags while the low fault frequency of underground cable MV networks and short MV feeder lengths contribute to low sag frequencies. In addition in urban areas, the strong transmission system prohibits sags caused by faults behind the neighbouring substations to be experienced in other MV networks.
- The HV line length per EHV/HV substation varies considerably and this is the major reason for the different voltage sag frequencies caused by 110 kV system faults.

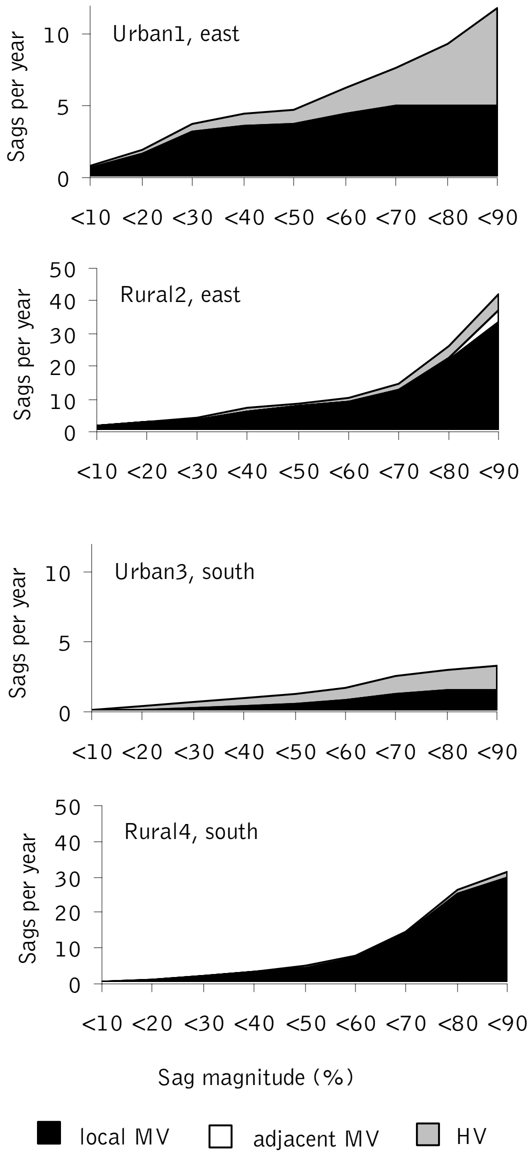

*Fig. 10. Calculated sag distributions (Publication V).*

## 4.3 Measured voltage sag distributions

Long-term measurements have been performed at two HV/MV substations in the middle part of Finland supplying rural areas with only overhead lines. In the substation areas where the measurements were performed, an autoreclosure sequence is used to clear temporary faults. The distance between the substations is about 200 km. Substation *Rural* 5 supplies five MV overhead line feeders with a total feeder length of 200 km and has an unearthed neutral. The measurements started in June 2002 and altogether 450 faults have been analysed. Substation *Rural* 6 has two main 110/20 kV transformers. However, the measurements from *Rural* 6 include the events observed in an MV network supplying only five MV overhead feeders of total feeder length 749 km with a compensated neutral. At this substation, the measurements started in August 2003 and a detailed analysis of altogether 1000 faults have been performed. Based on the measurement arrangements the faults that occurred in the transmission system could not be distinguished from MV faults occurring in the neighbouring MV systems. For example, single-phase earth faults on the transmission system and two-phase short circuits in the neighbouring MV systems have the same appearance at the measurement location. Fig. 11 presents the sag distributions measured at the two substations in 2004.

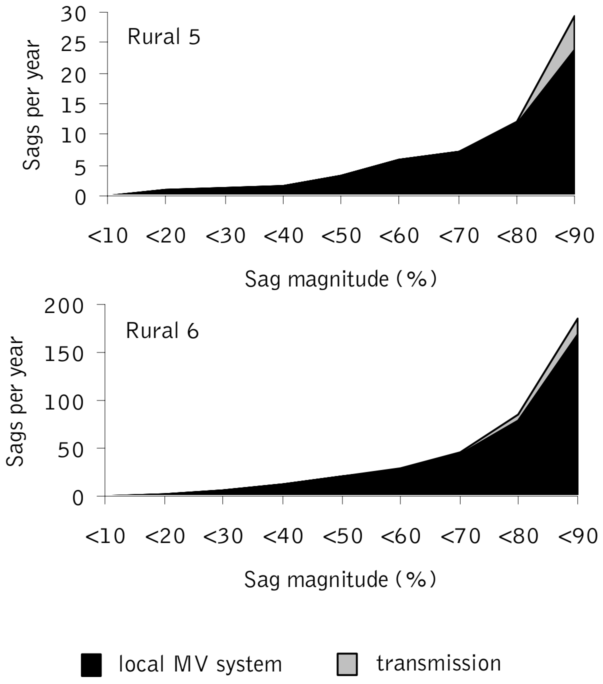

*Fig. 11. Measured sag distributions in 2004.*

The shapes of the measured rural distributions are similar. MV faults occurring in the local MV system make up most of the experienced faults. The annual number of voltage sags in these two substations is quite different. Substation *Rural 6* supplies almost four times the feeder length of Substation *Rural 5*. In addition, an annual variation exists – for example, substation *Rural 6* experienced exceptionally hard lightning storms during 2004 (Publication VII).

## 4.4 Survey and discussion

A widely used method for voltage sag calculations is the method of fault positions (Conrad et al. 1991, Bollen 1996, Qader 1997, Bollen 1999). When applying the method of fault positions, a large number of faults is generated throughout the power system and the reliability data of the power system is linked to the fault calculation results. Applying long-term reliability data to the method of fault positions results in long-term average or mean values for voltage sag distributions. The generating of different types of faults and the calculation of the resulting sagged voltages is a straightforward task utilising basic power system calculations. These calculations can be performed assuming constant values for

- distances between fault positions
- fault frequencies of various power system areas
- pre-fault voltages (generation and load patterns of the network)
- mix of various fault types
- mix of various fault clearing sequences
- fault resistances
- fault durations

or different variations may be applied.

Different approaches can be used for the selection of fault positions. In principal, increasing the number of fault positions improves the accuracy of the calculation but, on the other hand, calculation time may significantly increase. Typically, the buses in the network are fault positions. In addition, the lines could be divided into several fault sections, for example, 1% of the line length (Alves and Fonseca 2001) or into equal lengths, such as 1 km (Daniel 2004), etc. For this thesis (*Chapter 4.2 Calculated sag distributions*), MV fault positions were chosen to be every 100 m. Generally, shorter distances between fault positions can be applied in areas where the fault frequency is higher.

The input data for network reliability has its challenges. A basic assumption is that the number of faults is proportional to the feeder length and is the same over the whole voltage level in question. This assumption has also been used in this thesis (*Chapter 4.2 Calculated sag distributions*). The accuracy of voltage sag distribution calculations can be considerably improved by using different fault frequency data for various power system areas. Renner (2002) showed an example in his calculations where certain lines of the power system were particularly vulnerable to faults caused by lightning. The fault frequency of these lines was about six times the average fault frequency of the modelled area. Instead of using constant values for fault frequencies, various non-uniform distributions could be applied. Milanovic et al. (2005) researched the influence of the modelling of the fault frequency distribution (uniform, normal, exponential) along transmission lines on the assessment of the number and characteristics of voltage sags. It was shown that the choice of the fault distribution type had a considerable influence on the number and characteristics of voltage sags.

Detailed data considering the shares of various fault types is difficult to obtain. Generally, single-phase earth faults are the most typical and three-phase short circuits the rarest, as is used and reported in the voltage sag calculations made by Lim and Dorr (2000), Sikes (2000), Martinez and Martin-Arnedo (2004). In this thesis, constant shares of various fault types have been applied to overhead line and underground cable areas as well as to each voltage level (*Chapter 4.2 Calculated sag distributions*).

The switching status, generating and loading patterns influence the sag distribution. In distribution systems, the stronger the source, the higher the remaining voltages are. Local generators in distribution networks increase the fault level. Higher fault levels typically mean a stronger network which may exhibit an improved quality of power supply. A local generator also keeps up the voltages at the local buses during remote faults by feeding into the fault. Qader (1997), Milanovic et al. (2000), Milanovic and Gnativ (2001), and Olguin (2003) present the influence of network topology and embedded generators on voltage sag propagation. The results showed an important consequence of the meshed construction of transmission systems; the more interconnected the system is, the larger is the area affected by voltage sags following a short-circuit fault and the higher is the number of voltage sags per bus. The importance of using the appropriate pre-fault voltages received from load flow studies is emphasized. In an example from Milanovic et al. (2000), it was found that differences in the calculated number of sags were on average, for three-phase faults, about +/- 10% when using nominal or real pre-fault voltages. This is especially important in rural power distribution areas where the real pre-fault voltages at remote buses may be much lower than rated. In this thesis (*Chapter 4.2 Calculated sag distributions*), load currents were neglected. This means more optimistic results for voltage sag distributions. Especially in rural power distribution networks, the customers supplied by long feeder lines may experience voltage drops of several percent in normal loading conditions. When a short circuit fault occurs and the voltages of the substation busbar are sagged the customers at the far end of the feeders experience the sagged voltage of the substation busbar minus the normal voltage drop caused by the load currents. The customers at the far end experience a more pessimistic voltage sag distribution than is experienced in the vicinity of the substation busbar (Styvaktakis 2002).

The network is modelled using the impedances of the network components. In particular, the impedances representing the fault and the source are variable.

Typically it is assumed that the fault impedance has a value of 0 Ω. This yields the most pessimistic results in voltage sag distributions. In Publication II, the fault resistance seen in the overhead line networks was modelled assuming the resistance of an electric arc. In that situation, the sag frequency of sags $U_{sag} < 50\%$ was about halved. In other calculations presented in this thesis, a fault resistance of 0 Ω was applied. Martinez and Martin-Arnedo (2004) applied a non-zero value for fault resistance but reported difficulty in determining the appropriate value when the fault arc varies with time and depends on the type of the fault.

As presented above, constant values as well as various distributions can be applied to the method of fault positions. However, a major challenge is faced when determining the most appropriate distribution for each characteristic and network in question. Further, using a constant value for the distance between fault positions was discussed above. Another question that arises, is what constitutes a sufficient number of fault positions. For this purpose, Lim and Strbac (2002) and Olguin (2005) have presented an approach where the probability density function of voltage sags caused by faults across the network is presented. Monte Carlo simulation could also be applied. The simulation provides approximate solutions to a problem by performing statistical sampling experiments. The sag distributions are calculated using random numbers to model the behaviour of stochastic variables. Calculations are repeated many times, each calculation being independent from the others. The error of one single calculation is never zero but it reduces with increasing the number of simulations. The results of all the tests are then averaged.

Chapters 4.2 and 4.3 presented sag distribution with data concerning the origin of voltage sags. In this thesis, the main contribution to sag distributions was found to originate from the supplying MV system, especially in MV overhead line areas. Lamoree et al. (1994) and Kjolle et al. (2003) reached the same kind of result, but in Bollen (1996) the main origin for voltage sags was considered to be the transmission system. Similarly, the sag distribution can also show the contributing fault types that make up the sag distribution. Olguin (2003) showed that single-phase earth faults are the main contributing fault type at the voltage level of the fault event. However, the contribution of different fault types did not entirely follow the probability distribution of faults. The affected area of various fault types explained the difference.

In addition to calculating the whole sag distribution for a certain network location, other indices have been developed. Gnativ and Milanovic (2005) introduces new indices for the assessment of voltage sag propagation. The *Sag Propagation Index* is calculated by dividing the number of power system buses experiencing a lower sag magnitude than a threshold value with the total number of buses of the network of interest. These indices are calculated for different power system constructions, such us radial, medium meshed or meshed network. Further, an *Average Sag Propagation Index* can be determined by calculating the index for several fault cases and calculating the average of the indices. The index of asymmetrical faults includes the number of phases affected by voltage sags. For example, if only one of three phases experiences a lower value than the threshold value, the sum in the nominator is increased by one and the sum of the denominator by three.

As discussed above, there are several aspects to be taken into account when applying the method of fault positions. In the calculations performed in this thesis, an extended method of fault positions using long-term reliability data has been used. In Chapter 5, this model is used to find the relative changes in voltage sag distributions when certain network improvements are carried out. Thus, the main focus in this thesis was to find a basic, simply applicable tool for voltage sag calculations and the developed extended method of fault positions fulfilled these requirements.

# 5 MEANS TO LIMIT THE EFFECTS OF VOLTAGE SAGS

Voltage sags may cause significant economic losses. Thus there is a definite need for the knowledge and means that are needed to limit and mitigate voltage sags. In principle, the methods of reducing the effects of voltage sags can be categorized into measures, for example, (Conrad et al. 1991), (Bollen 1999)

1. to reduce the number of faults (especially short-circuit faults) in the power system
2. to modify the power system to minimize the influence of voltage sags including steps
   - to restrict the sag propagation
   - to support the maintaining of a higher remaining voltage during the sag
   - to decrease the sag duration
3. to use voltage sag mitigation equipment between the power system and the sensitive load
4. to improve the immunity of the load

This thesis concentrates on reducing the number and severity of faults by conventional means and by utilizing regular power system components in MV power distribution networks (points 1 and 2 of the list presented above). Separate voltage sag mitigation equipment is out of the scope of this thesis, as are improvements carried out with the immunity of the load. However, below is a short introduction concerning these aspects.

Equipment, such us uninterruptible power supplies (UPS), motor-generator sets, constant voltage transformers, and static tap changers, can be used for voltage sag mitigation. With the competitive development of power electronics, the equipment associated with custom power technology has been introduced for various power quality issues. For voltage sag mitigation, the custom power technology is based on switching the load to another supply, on injecting missing voltage from an energy storage, or on injecting missing voltage by increasing the line current (Pohjanheimo 2003).

Improving the equipment immunity is directed to the manufacturer of the equipment and is typically out of reach of the customer. From the process or factory point of view, a thorough inspection of the immunity of the whole functional entity, comprising of, for example, contactors, relays, sensors, computers, motors, etc., is needed (Pohjanheimo 2003).

As mentioned above, this thesis concentrates on the means of decreasing the probability of faults (especially short circuits) and limiting the severity of sags. The solutions studied are to be implemented in an MV power distribution network. Chapter 5.1 introduces general means for voltage sag mitigation by reducing the number of faults occurring in the power system and Chapter 5.2 treats solutions in the power system structure. The efforts presented in these two Chapters may, to some extent, have overlapping characteristics. Chapter 5.3 deals in more detail with the voltage sag mitigation effects of various overvoltage protection solutions for distribution transformers. Chapter 5.4 covers MV feeder types and Chapter 5.5 distribution automation.

## 5.1 Reducing the number of faults

To reduce the number of sustained interruptions has always been one of the main goals in the planning and operation of power distribution networks. This is a task where power distribution companies, always taking into account the safety issues, balance the investment costs of network development and improvements, and costs caused by interruptions, sags and poor power quality. The goal of reducing the number of faults concurs with the aim of voltage sag mitigation. If there are less faults occurring in the power system, there will be less voltage sags caused by faults. To avoid faults and sags various suggestions for power system improvements are advised, such as (Bollen 1999, Stones and Collison 2001)

- choosing alternative component types, for example
    - underground cables instead of overhead lines
    - covered conductors instead of bare overhead lines
    - surge arresters instead of spark gaps
- installing shielding wires
- increasing insulation level
- having power system components of high quality
- implementing strict policy for maintenance and inspection
- carrying out careful tree trimming
- as in normal operation, especially in maintenance and repair work, careful planning of working schedules to ensure the safety of personnel and to avoid accidents and faults

## 5.2 Solutions in the power system structure

Power system characteristics strongly affect sag propagation. From a voltage sag point of view, the meshed structure of a power system is a disadvantage and a radial system would be preferred (Qader 19979, Olguin 2003, Gnativ and Milanovic 2005). An efficient way to limit the sag propagation is to split buses and substations in the supply path to limit the number and length of feeders in the affected area. Fig. 12 shows an example. With a stiff supplying network the sags appearing behind a neighbouring supply transformer are no longer experienced as voltage sags in the adjacent distribution network. Sag-sensitive customers can be supplied by their own transformers, the size of their MV networks kept limited and special efforts focused on their MV networks to avoid faults. In addition to voltage sags, the two parallel MV distribution networks presented in Fig. 12 might be quite different in the sense of other power quality issues, such us interruptions, undervoltage and harmonics, as well.

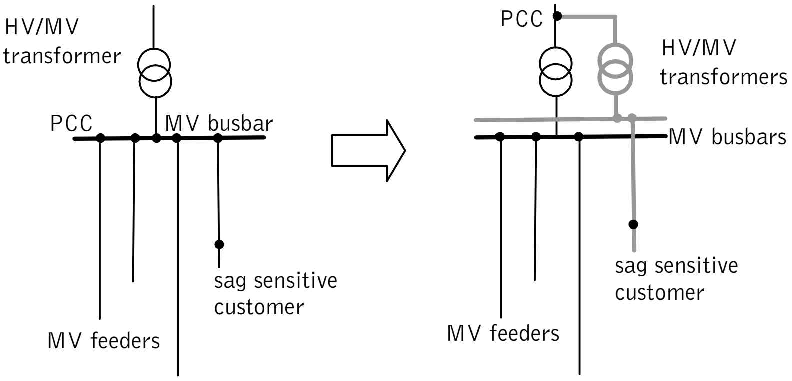

*Fig. 12. Dividing the distribution network to limit sag propagation.*

Feeding the sensitive load from two or more substations or having a generator station near the load could support the voltage during a fault (Gnativ and Milanovic 2000, Gnativ and Milanovic 2005). However, the number of faults may be increased because of increased exposed feeder lengths or power system components prone to faults and misoperation.

Sag severity can be limited by increasing the electrical distance to the fault, for example, by installing current limiting coils in strategic places. In radially operated networks, the load side of the PCC should represent a high impedance and the supplying side a low impedance. However, when rating the main power system components, such us the HV/MV transformer or MV feeders, other operational constraints, for example, power losses, voltage drops or protection characteristics, typically determine the rating of these components – their influence on voltage sag characteristics is minor and represents an inefficient tool for voltage sag mitigation. In addition, the characteristics of sag influence may cause conflicting objectives in power system planning. For example, high impedance on the load side would mean a high impedance MV feeder. This means, for example, increased voltage drops and higher power losses in the network - features that are valued as negative in power system planning and operation.

Daniel (2004) showed an example where, instead of a 12 kV MV distribution system, a 35 kV system has been taken into use. Power distribution companies typically justify utilizing higher voltage systems. With the higher MV voltage levels, however, a considerable number of customer complaints caused by voltage sags were reported. The low impedance of 35 kV distribution feeders was the most substantial factor that caused these problems. The study resulted in recommendations for the power transformer impedance to be reduced, the fault duration to be shortened (smaller fuse size, current limiting fuses), the number of lightning faults to be minimized by installing additional lightning arrestors and the duration of three-phase faults to be shortened. It was also emphasized that faults occurring within the first couple of feeder kilometres leaving the substation are the most critical. Gomez and Morcos (2001) also emphasize the minimizing of the duration of faults for voltage sag mitigation purposes. In addition, single-phase tripping is listed.

The characteristics of typical distribution networks contribute to certain sag characteristics. Publication I presents typical sag distributions calculated for various Finnish power distribution networks, explaining the contributing rural/urban power system characteristics. Typically, urban customers experience less sags than rural customers (Publication I, Short et al. 2003, Kjolle et al. 2003). Thus, in principal, by adopting some urban practices in rural areas, the sag distribution can be improved.

## 5.3 Overvoltage protection of power distribution transformers

Lightning and various switching operations cause overvoltages. In addition, a common cause of overvoltage in networks having an unearthed or compensated neutral is a single-phase earth fault - during single-phase earth faults, the phase-to-ground voltages of the sound phases reach the value of phase-to-phase voltages.

In particular, steep overvoltages caused by lightning may be damaging to the windings of power distribution transformers and so overvoltage protection has been installed. In the 1950s spark gaps were introduced for overvoltage protection. A spark gap has one metallic rod connected to a phase conductor and a second rod connected to earth. Further, in the 1970s, double spark gaps were taken into use. In the double spark gap, an electrode at free potential (a bird spike) is located between the metallic rods to avoid the unintentional operation of a spark gap (Fig. 13a). During the same decade, the first surge arresters (Fig. 13b) were introduced. In the last thirty years, the major change in the field of surge arrester technology has been the shift from gapped silicon-carbide arresters to gapless metal oxide surge arresters. In addition, combinations of spark gaps and surge arresters, such us externally gapped metal-oxide surge arresters, are in use.

In rural areas supplied by overhead lines, distribution transformers are typically pole-mounted and one MV feeder can supply dozens of distribution transformers. Every distribution transformer has three overvoltage protection devices, one on each phase. A typical placement of overvoltage protection equipment is across the MV terminals of the power distribution transformer or next to the disconnector of the distribution transformer. For overvoltage protection, smaller, cheaper transformers are equipped with spark gaps and larger, more expensive transformers with surge arresters. In Finland, the established practice for the selection of overvoltage protection type has been the transformer size; transformers of 200 kVA or smaller have been equipped with spark gaps and larger ones with surge arresters (SFS 1987).

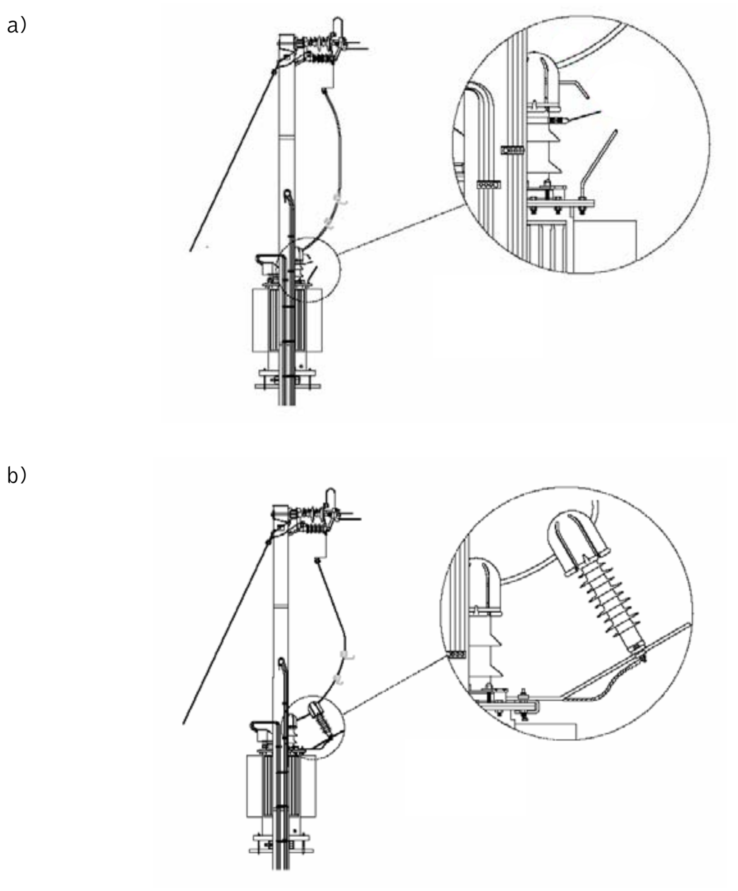

*Fig. 13. Overvoltage protection of a pole-mounted power distribution transformer using a) spark gaps, b) surge arresters (Headpower 2003).*

From a component point of view, the major advantages / disadvantages of various overvoltage protection types arise from the open (spark gap) or closed (surge arrester) structure. The major advantages of the use of spark gaps are that they are cheap and the structure is simple. A spark gap can be visually checked, at least to some extent. On the other hand, the open air structure makes spark gaps prone to atmospheric circumstances (temperature, air pressure, wind, rain, humidity, dirt), which partly contributes to the wider dispersion in protection levels. A spark gap can unintentionally be triggered caused by an external cause, like a small animal or a tree branch. In addition, when an electric arc is burning in one spark gap, it gets gradually longer, the surrounding air is ionized and makes it possible for an adjacent spark gap to also spark over.

Surge arresters have a closed structure and are thus not prone to atmospheric conditions, unintentional operations caused by small animals or tree branches, or to neighbouring surge arresters. On the other hand, they are more expensive and the identifying of a damaged surge arrester may be laborious.

From the voltage sag point of view the operation of different types of overvoltage protection equipment has one major difference. When one, two or three spark gaps operate, the power system responds as if experiencing a fault (Fig. 14). If one spark gap operates, a single-phase earth fault enters the system. When two or three neighbouring spark gaps operate at the same time, a two- or three-phase-to-ground short circuit is experienced. The event may initiate in one spark gap as a single-phase earth fault, but then spread within a few cycles to the neighbouring spark gap causing a two-phase-to-ground short circuit. On the contrary, no fault or sag is experienced when one, two or three surge arresters are activated at the same time.

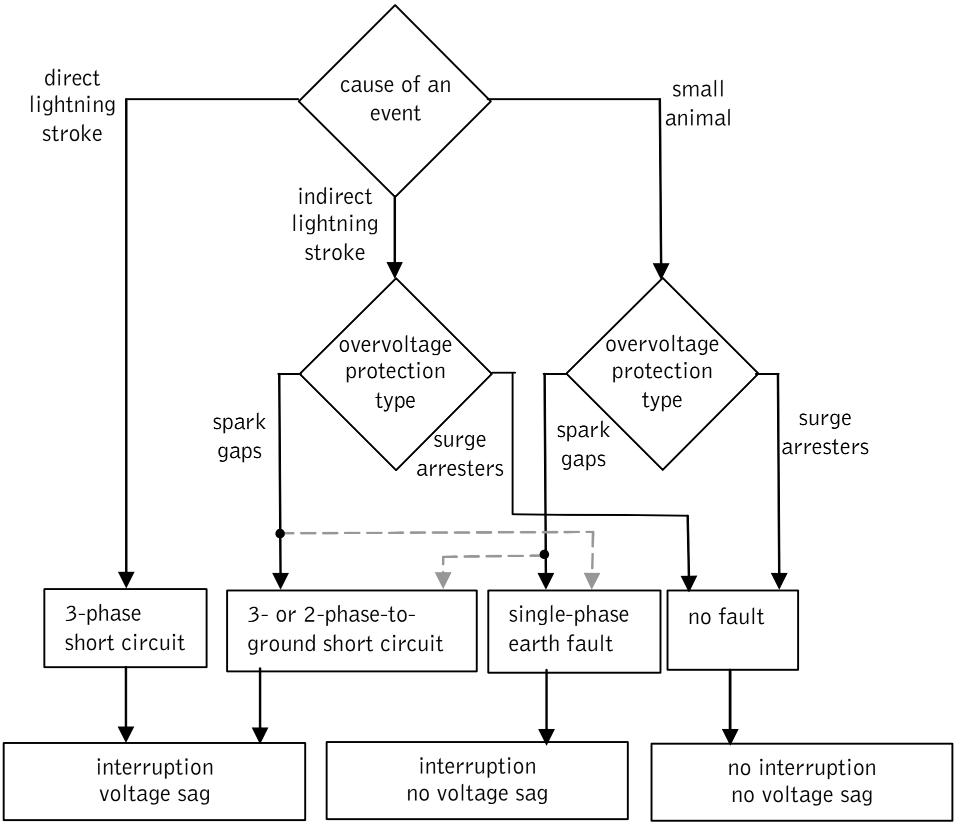

*Fig. 14. The influence of the cause of a disturbance and overvoltage protection type on fault types and system behaviour (Publication VIII).*

The possibility of a developing fault event in spark gaps is annoying. Fig. 15 shows a pole-mounted power distribution transformer. When an electric arc is burning in one spark gap, it is gradually extended and hence is prone to spread also to the adjacent spark gap. The bare, energized conductor parts of neighbouring phases are, in the vicinity of a power distribution transformer, closer to each other than elsewhere along the feeder length.

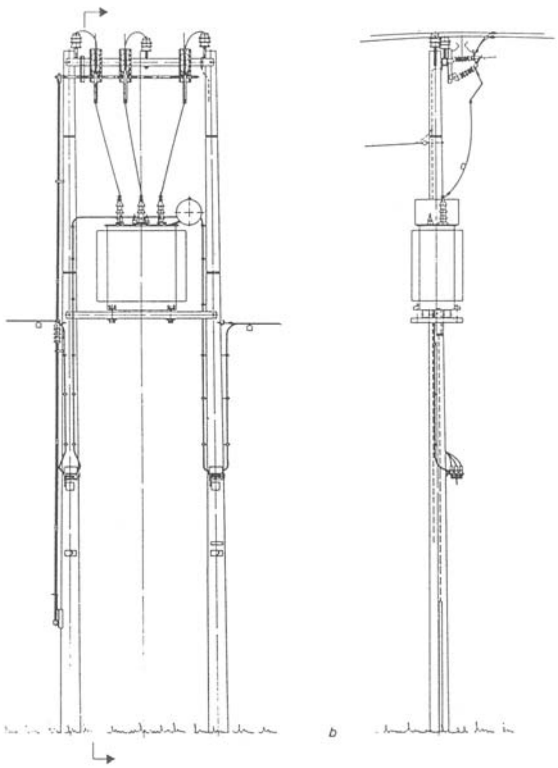

*Fig. 15. A pole-mounted power distribution transformer (SFS 1987).*

The system behaviour caused by the operation of overvoltage protection is presented in this thesis. The question is approached according to the triggering reason of the overvoltage protection equipment (Fig. 14). The main study is introduced in Publications VI, VII and VIII.

Publication VI studies the unintentional operation of spark gaps caused by an external cause and the probability of the fault developing from one spark gap to a neighbouring spark gap. In the measurements, the characteristic of a developing fault type was found to represent a remarkably high share (10%) despite that according to the presented theory, the probability should have been lower (0.4%). The electric arc burning in spark gaps probably contributes to this difference. The developing fault event in spark gaps is highly undesirable because short circuits are stressful faults always causing, in addition to an interruption, voltage sags to also be experienced in the whole substation area. The fault frequency of surge arrested feeders was reported to be 16% of the fault frequency of spark gapped feeders.

Publication VII studies the operation of overvoltage protection during lightning storms. A significantly high proportion of the annual MV faults may occur during a couple of lightning storms and are worth a special study. Direct lightning strokes are severe faults that most probably cause a three-phase short circuit somewhere along the MV feeder length no matter what the overvoltage protection type is. However, the majority of overvoltages caused by lightning are induced overvoltages caused by lightning strokes in the neighbourhood of the feeders. Publication VII shows that, during lightning storms, it is not single-phase earth faults, but short circuits with and without ground connection that represent the majority of faults. This means that in the case of overvoltages during lightning strokes typically two or three neighbouring spark gaps operate at the same time. The fault frequency of surge arrested feeders was reported to be 9% of the fault frequency of spark gapped feeders.

Publication VIII links an economic aspect to the discussion about the choice of overvoltage protection. The customers' interruption and voltage sag costs were included in the study. One of the major results was that the costs experienced in the surge arrested feeders were primarily due to sags caused by faults occurring in the neighbouring spark gapped feeders. Thus, the whole substation area suffered because of the high fault frequency of the feeders having spark gaps only. This result serves as a reminder to proceed carefully when planning improvements that address voltage sags. Similar to Publication II, Publication VIII showed especially high costs originating from voltage sags.

Fig. 16 and Fig. 17 sum up the presented theory and the long-term measurements. From the voltage sag point of view, the choice of overvoltage protection of power distribution transformers has a more important role in limiting the influence of voltage sags than has been considered before. Interruptions and voltage sags belong together. A spark gap operation means an interruption. A multi-phase operation of spark gaps means, in addition, that voltage sags will be experienced in the whole substation area. From an interruption and voltage sag point of view, the use of surge arresters is highly recommended.

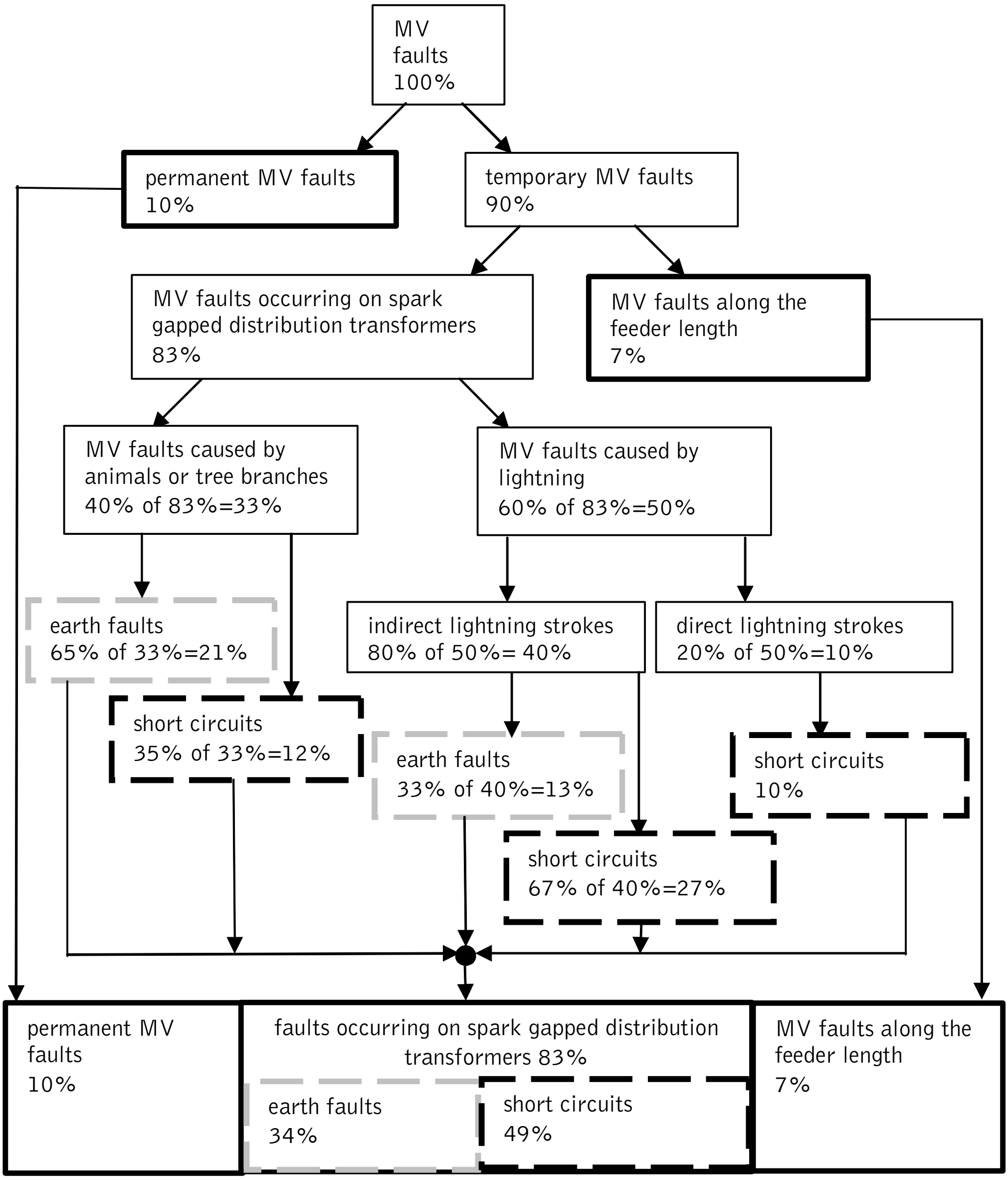

*Fig. 16. The categorizing of the measured faults in a network that has spark gaps for the overvoltage protection of power distribution transformers.*

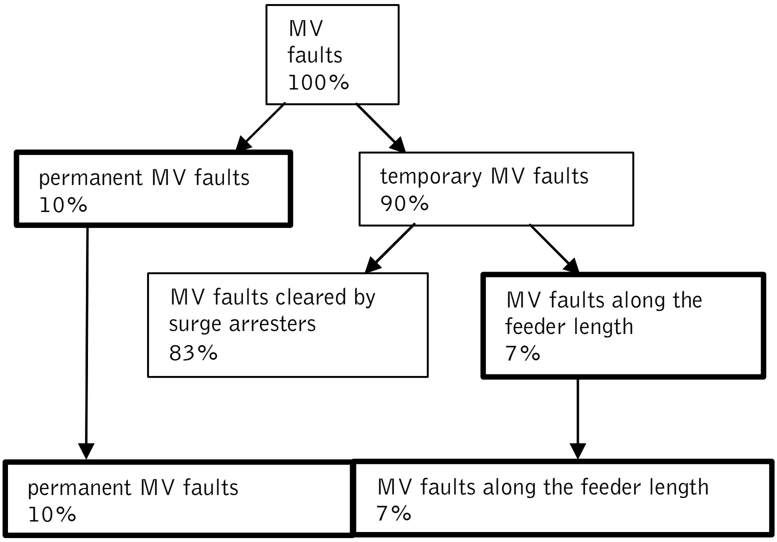

*Fig. 17. The categorizing of the measured faults in a network that has surge arresters for overvoltage protection of power distribution transformers.*

## 5.4 Medium voltage feeder types

### 5.4.1 Several feeder types in one substation area

MV networks are typically built with bare overhead lines in rural areas and with underground cables in cities. From the voltage sag point of view, MV networks constructed with only underground cables are preferable. Underground cables are superior to bare overhead line networks because of their low fault frequency. Considering sag influence, short circuit faults occurring in underground cable networks with typically smaller line impedance contribute to low remaining voltages. However, a more significant aspect than the lower remaining sagged voltages is that faults in underground cable networks are rare events and thus the number of sags is low.

In many areas, power distribution networks are built step by step following the overall development of the society - villages develop into small towns and then into bigger cities. Areas that were in the beginning supplied by only overhead lines are gradually changing to underground cables (Fig. 18). This development can take decades. During the course of years, it is typical in areas like city outskirts that mixed (both bare overhead lines and underground cables) feeder structures are used in one substation area or along one feeder length. From a scenic, land use, or reliability point of view, the development towards underground cable areas is preferable. However, from the voltage sag point of view this phase of the development of mixed structure might have negative consequences.

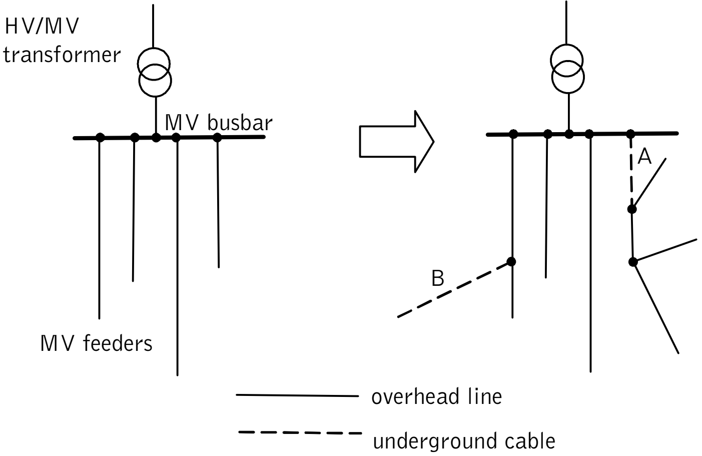

*Fig. 18. The development of an MV network from a bare overhead line network to a network consisting partly of bare overhead lines and partly of underground cables.*

Publication I studied this in more detail. In particular, a case where a part of the main feeder leaving the supplying substation was replaced with an underground cable resulted in an unpredictably high number of harmful sags. From the voltage sag point of view, the problem with such a replacement is that the relatively small share of the total feeder length of the new underground cable in the vicinity of the substation brings the rest of the overhead line MV network with its higher fault frequency electrically closer to the PCC (case A in Fig. 18). The further the replacement is from the supplying substation, the less sag influence it has (case B in Fig. 18). In terms of voltage sags, when considering the whole life cycle of an MV network development, the phase of mixed structure means a worsening step before developing to a pure underground cable city network.

The above mentioned study represented a case where the replacement was carried out along one feeder length. The same concerns the whole substation area. Typically, a sag sensitive customer experiences sags that originate from faults occurring in the neighbouring MV feeders. The number of interruptions can be limited by supplying the customer with an underground cable but if there is a sag-sensitive customer, overhead lines or feeders with mixed feeder types should not be accepted anywhere in the substation area in question.

### 5.4.2 Covered conductors

In addition to the basic feeder types of underground cables and bare overhead lines, the use of covered conductor lines has been expanding from the 1970s. Covered conductors are an alternative to bare overhead lines. A covered conductor system resembles in principle the conventional bare conductors. The conductors are covered with a thin layer of high dielectric strength XLPE (Fig. 19). The major advantages in using covered conductors are their reliability in very severe conditions and the minor use of land for feeder corridors.

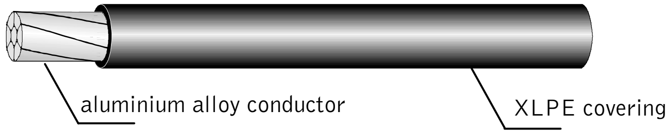

*Fig. 19. The covered conductor (Pirelli 2003).*

Because of the covering, the conductors may temporarily touch each other or trees or tree branches. The covering allows the phase spacing to be reduced to one third of bare overhead lines. Also, the width of the line corridor can be reduced. Covered conductors have been proven to sustain, for example, the weight of fallen trees for days, both mechanically and electrically. This ability is advantageous during major storms when a power distribution company may have dozens, if not hundreds of trees lying on feeders waiting for removal. If the covered conductor is not electrically or mechanically damaged, power distribution companies have more freedom to reschedule the repair work and continue the supply.

As far as voltage sags are concerned, the use of covered conductors instead of bare overhead lines is preferable, if it results in a lower number of faults (especially short circuit faults) with higher remaining voltages during faults. Publication III presents the results from such a study. There is no marked difference in the resulting sag magnitudes and the main contribution becomes from the lower fault frequency. Analysis of statistics including 2650 faults in MV networks with partly covered conductors was performed. The networks had both spark gaps and surge arresters in use. In the study, the fault frequency of permanent faults in covered conductor feeders was 72% of the fault frequency of bare conductors. However, this number also included those faults where no instant repair was needed. When removing these faults, the fault frequency decreased to 20%. Hart (1994) and Penny (1997) reported that for permanent faults the fault frequency of covered conductor feeders is 25-50% of the fault frequency of bare overhead line feeders. In addition to the lower number of permanent faults, the decrease in the number of faults cleared by autoreclosure sequence was considerable. Publication III shows results from a study where all the permanent faults on covered conductor feeders were single-phase earth faults. From a voltage sag point of view, this result is highly appreciated given that, due to Dyn transformer connections, single-phase earth faults on the MV side are not seen as voltage sags on the LV side.

## 5.5 Distribution automation

Generally, automatic operations are necessary to isolate faults in a network in the least possible time in order to minimise damage to individual items of equipment, staff and public. Distribution automation includes various functions, such as protection, substation control, sophisticated fault management and distribution system state monitoring. To perform these functions distribution automation uses various power system components, substation automation, feeder automation, telecontrol, telecommunication and information systems (Fig. 20).

The first steps in distribution automation included basic measurements of the power system status and the functions to safely and reliably isolate the faulted power system part from affecting the rest of the system. Measurements and automatic power system operations were typically performed at the HV/MV substation. As a consequence of the development of electronics, telecommunication, sensors, and also the development of the traditional power system components, distribution automation offers more possibilities to perform remote monitoring and control of distribution automation equipment and processes that are geographically dispersed over wide areas. The field of automation applied in electrical distribution networks is manifold and the degree of automation in electrical distribution networks is constantly growing.

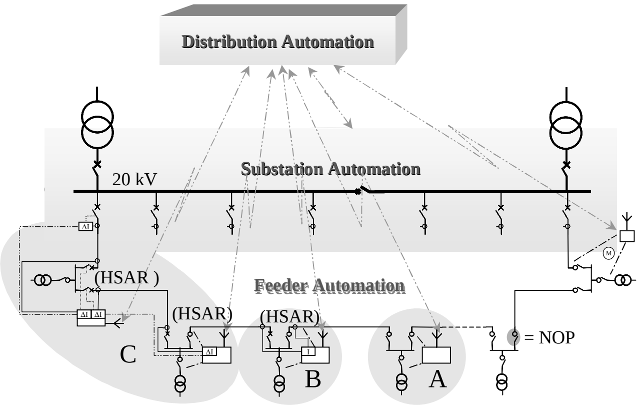

*Fig. 20. Network model showing automation solution alternatives (HSAR – High-Speed Auto-Reclosing, NOP –Normal Open Point) (Publication IV).*

While distribution automation offers new tools for fault management it inevitably also has an influence on voltage sags. Traditionally, in a radially operated network, there are circuit breakers for each MV feeder at the HV/MV substation. Only circuit breakers are able to open a circuit carrying a fault current. When a fault enters the MV system, the protection trips the circuit breaker of the faulted feeder to be opened and all customers supplied by this faulted feeder will have an interruption. In addition, a voltage sag may be experienced in the whole substation area. In the case of a permanent fault, the faulted section of the feeder can be found by trial switchings, using sectionalisers, fault indicators and the various computational tools which may be used to determine the fault distance. After finding the faulted section of the feeder, it is isolated by opening the surrounding disconnectors and back-up supplies are arranged to as many customers as possible.

With regard to voltage sags, distribution automation presumably aims with all its sophistication to reduce the sagged area caused by faults, lower the number of repetitive sags caused by a single fault event, maintain a higher remaining voltage during the fault and shorten the duration of the disturbance. With distribution automation the area experiencing a fault (an interruption) can be restricted. However, a voltage sag is already experienced during the early phases of a fault, so the affected area of voltage sags is not necessarily limited. The voltage sag magnitude might also be difficult to influence by means of distribution automation. However, the number of repetitive circuit breaker operations can be limited when the fault location is faster and more reliable. In addition, the voltage sag duration may also be shortened.

The development of MV networks concerning fault management and sag influence was studied in Publication IV and includes the following network structures for fault management

A. a radially operated MV network with circuit breakers at the substation and manually operated disconnectors along the feeder lengths
B. a radially operated MV network with circuit breakers at the substation and remotely operated disconnectors along the feeder lengths
C. a radially operated MV network with additional circuit breakers at the secondary substations along the feeder lengths
D. connecting two radially operated MV feeders at the far end as one ring and having circuit breakers at the substation and also along the ring

In cases A and B, the sag distributions were the same. The customers experience sags caused by faults occurring in the neighbouring feeders. In case C, the functionality was increased by also having circuit breakers at the boundaries of the protection zones along the feeders. In case C, the sag distribution is different. Again faults occurring in the adjacent feeders cause sags to the whole substation area. In addition, the faults occurring in the customer's feeder may cause sags to the customer in question. When a fault occurs in the same feeder where the customer is, the customer experiences an interruption or a voltage sag depending on the relative location of the fault and the customer. In this case, compared to a radially operated network that only has circuit breakers at the substation, the number and the duration of interruptions is decreased while the sag frequency is increased. In case D, two radially operated feeders were switched at the far end to form a simple ring. Now more severe sags were experienced because the ring structure means a lower impedance.

The results showed that increased automation and also ring construction increase the number of sags and especially the number of the most severe sags. Thus, this development in the network structure would mean worse power quality in the sense of sags despite the decreased number and duration of interruptions.

The costs of interruptions and voltage sags were also calculated for the different operation modes and distribution areas. The costs of interruptions decreased and the costs of sags increased with increased automation and the ring structure. In urban areas, the total costs were decreased. Thus, in urban areas, investments in automation or the use of looped networks may be justified by the savings in the total costs of interruptions and voltage sags.

The high share of costs of voltage sags in cases of increased automation or looped network configuration encourage the finding of different tailored solutions to serve sag-sensitive customers. In addition, the cost of voltage sags and interruptions are only one aspect when considering the advantages and disadvantages related to increased automation and different network structures. Other features, like voltage drops, power losses, and the cost of each option should be evaluated together to be able to decide the superiority of different solutions.

## 5.6 Discussion

The origin and characteristics of voltage sags are essential data when finding solutions for voltage sag mitigation. This chapter has concentrated on MV networks to find out the influence of conventional network structures and regular power system components on voltage sags. In principal, when the fault characteristics and the affected area of faults is influenced, this also has an effect on voltage sags. This chapter presented the effect of

1. individual HV/MV transformers for sag-sensitive loads
2. overvoltage protection of power distribution transformers
3. MV feeder types
4. distribution automation

on voltage sag characteristics. When limiting the sag influence of MV faults, sag-sensitive customers can be supplied by their own HV/MV transformers and further, special efforts can be made to prevent and limit fault occurrence in the customer's own MV network. An MV network should be built using underground cables only to have as few faults as possible. However, in the case of an overhead line MV network, surge arresters instead of spark gaps are strongly preferred for the overvoltage protection of pole-mounted power distribution transformers. Voltage sag mitigation efforts should especially be addressed to the vicinity of substations to lower the probability of the most serious voltage sags. However, this statement is not meant to imply that only a part of the overhead lines should be replaced with underground cables in the neighbourhood of substations.

It also was shown that not necessarily all stages in the development of the power distribution system mean improvements in the sense of voltage sags. When mixed networks having both underground cables and overhead lines as well as distribution automation generally advance the development of the distribution system, in the sense of voltage sags the achievements may be negative. The problem with mixed networks from the voltage sag point of view is the low impedance of underground cables. In the cases under study, automation has widened the area affected by voltage sags.

# 6 CONCLUSIONS AND CONTRIBUTIONS OF THE THESIS

When the importance of voltage sags is rapidly increasing, power distribution companies should also have deeper understanding of the voltage sags experienced in their distribution network as well as of the network characteristics that influence the sag distribution and propagation. Contributions of this thesis have been

- the developing of a simple method for voltage sag analysis which can be combined with the fault statistics,
- the analysis of voltage sag distributions in the Finnish power system and the presentation of results from calculated and measured voltage sag distributions,
- the findings on how several specific alternative network constructions affect the sag distribution.

A widely used method in voltage sag analysis is the method of fault positions. This thesis introduced an extension of this method to cover different fault types and fault clearing sequences still enabling the use of the basic fault calculations. This extended method was applied to the calculations of voltage sag distributions experienced in various power system areas of the Finnish power system. The developed extended method of fault positions offers a tool to evaluate the sag distribution with a limited amount of input data.

Results from long-term measurements were also presented. Measurements offer detailed voltage sag data relevant to the network point of concern. However, the problem with measurements is the long time needed and the challenges in extrapolating the results to another location or time.

Voltage sag distributions can be affected. Specific network solutions were researched in the context of voltage sags. From the voltage sag point of view, sag sensitive customers should be supplied by their own main transformer and special efforts should be focused on the MV network in question to avoid faults. In addition, significant improvements in the behaviour of overhead line MV networks were obtained from the use of surge arresters instead of spark gaps for the overvoltage protection of power distribution transformers. When considering MV feeder types, they can be listed from the worst to the best as pure overhead line networks, pure covered conductor feeders, pure underground cable networks. However, mixed networks may be detrimental in the sense of voltage sags. In addition, the effect of an increased level of distribution automation was studied. Despite the many improvements achieved with the implementation of distribution automation, voltage sag characteristics have tended to deteriorate. Thus, from a voltage sag point of view, the development of power distribution networks may exhibit negative as well as positive influence and more awareness of these affects is needed.

In this thesis, the main focus has been voltage sags. However, voltage sags represent only one aspect to be taken into account in the planning and operation of power distribution networks. Thus, voltage sag analysis should not be a separate part of power distribution planning but included as one, important element in a comprehensive power system analysis. Actually, power distribution systems already have a lot of data available for voltage sag calculations in their network information systems. As presented in this thesis, the reliability data of network components needs further research and study. By having more accurate statistics of the reliability of various power system parts, the accuracy of the voltage sag distribution can be improved. On the other hand, the economic calculations revealed the considerably high economic impact of voltage sags. This points out the possibilities of tailored solutions for sag-sensitive customers, who are possibly not so high in number.

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