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Voltage Sag Analysis Taken Into Account In Distribution Network Design

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Abstract--Voltage sag distributions were calculated for six different 20 kV electricity distribution systems. Results are highly dependent on the distribution system. The percentage of deep severe sags is much higher in urban systems while the annual number of sags is bigger in rural areas. AM/FM-GIS has proved to be an efficient tool in distribution system planning. Often costs are included in these studies. As a new development step sag analysis was introduced to be integrated to these tools. A pilot software has already been developed in this project.

***Index terms*--power distribution, power system modeling, power quality**

I. INTRODUCTION

A voltage sag is a sudden reduction in the supply voltage magnitude followed by a voltage recovery after a short period of time. Voltage sags are mainly caused by short circuits, overloads and starting of large motors. The importance of voltage sags has increased due to problems sags cause to many types of equipment. To be able to estimate the damage voltage sags cause to customers also new tools and analysis programs are needed.

Network information systems (AM/FM-GIS) (Automated Mapping/Facilities Management – Geographic Information System) are widely used in power distribution companies. These systems include tools for case-specific steady state analysis for different purposes, e.g. programs for load flow calculations, fault current analysis, load growth estimation and reliability analysis. Also voltage sag analysis could be included in this list of programs.

This paper presents typical voltage sag distributions calculated for Finnish rural and urban networks. Voltage sags propagate throughout the power system and a sag sensitive customer can experience sags caused by faults at the same, higher or lower voltage levels. In this paper the main interest is distribution companies and their possibilities in decreasing the impact of voltage sags. Thus only voltage sags caused by short circuit faults on MV radially operated networks and experienced by LV customers are studied.

Network characteristics have influence on voltage sag distribution. In this paper it is shown that while one investment may be justified e.g. in the sense of reliability the same investment may worsen the situation related to voltage sags. This is one basis to include sag analysis in network information systems. The platform used for network planning in power distribution companies and including voltage sag analysis is presented.

II. SAGS IN MV SYSTEMS

In power systems having isolated neutral voltage sags are mainly caused by short circuit faults. A short circuit fault on one radially operated distribution feeder causes a sagged voltage on the substation busbar. This sagged voltage is further experienced by all the customers supplied by the same HV/MV transformer.

To explain voltage sag characteristics a voltage divider model is often used, (1).

$$\underline{U}_{sag} = \frac{\underline{Z}_F}{\underline{Z}_S + \underline{Z}_F} * 1.0\text{p.u.} \qquad (1)$$

where $\underline{U}_{sag}$ is the remaining voltage during the sag, $\underline{Z}_F$ the impedance of the feeder from the substation to the fault place including the fault impedance, $\underline{Z}_S$ the impedance of the fault current path on the source side of the PCC (point of common coupling) [1], [2].

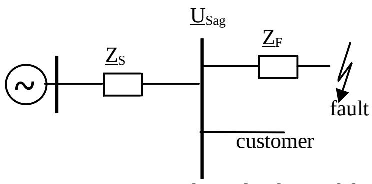

Fig. 1. Voltage divider model.

In this model load currents were neglected. The model can be used for the calculation of symmetrical three phase faults. In a case of unsymmetrical faults e.g. the calculation of symmetrical components should be included.

Not all fault types cause voltage sags. E.g. in neutral isolated or coil earthed medium voltage networks single phase to ground faults do not cause any voltage sags at the low voltage customer location.

It is also important to estimate how often customers experience sags. This estimation requires a probabilistic approach and network reliability data. The fault frequency rates of network components are combined with the sag analysis results [1], [2]. As a result a sag distribution (sag magnitude, duration, frequency) can be determined for each customer. Often a cumulative sag frequency of sags having remaining voltage below a threshold magnitude and lasting longer than a threshold duration is of interest.

III. VOLTAGE SAG DISTRIBUTION OF RURAL AND URBAN COMPANIES

Rural and urban networks have their typical network characteristics which further contribute typical characteristics of rural and urban voltage sag distributions. Below is discussed the effects of network characteristics on sag distribution caused by faults on the neighbouring MV feeders of the sag sensitive customer. Sags are less harmful if the remaining voltage during the sag is higher and if the sag frequency is lower.

Compared to rural areas urban areas have typically higher loading, more looped and stronger transmission system and larger transformers at HV/MV substation. Stronger source and larger transformers mean higher remaining voltage during a sag, (1).

Urban networks consist typically of underground cables having larger cross sections than rural overhead line networks. Larger cross section means smaller line impedance and thus lower remaining voltage during the sag, (1). On the other hand the lower fault frequency of underground cables means less faults and sags.

Urban HV/MV substations have more feeders per substation than rural ones. The more adjacent feeders the sag sensitive customer has the more feeder length is exposed to faults that cause the most severe voltage sags.

Feeder lengths are in urban areas typically shorter (<10 km) than in rural systems (feeder lengths may be tens of kilometers). The most severe voltage sags are caused by faults close to the PCC and thus the percentage of the most severe sags is higher in urban systems. The sag distribution of urban systems may lack the shallowest sags. In rural areas the longer feeder length increases the exposure to faults but the electrical distance tend to reduce the sag impact. The annual sag frequency is in rural areas higher than in urban areas. In addition in rural systems part of the total feeder length may be negligible in voltage sag analysis. In rural areas the share of the shallowest sags is typically remarkably higher than the share of the most severe sags.

In urban networks feeders have typically only a few branches. Branches increase the total feeder length and the length exposed to faults and sags. If the main feeder is tens of kilometers then branches at the far end of the main feeder can be electrically so far that their sag impact can be neglected. On the other hand branches close to the substation can remarkably affect the sag distribution. The closer the PCC the branches are situated the more influence they have on sag characteristics.

To conclude the above mentioned properties the source side of the PCC should be electrically strong and the load side of the PCC electrically weak and the size limited.

As case studies sag distributions were calculated using 20 kV data of six Finnish companies, four rural and two urban ones, Table 1 [3]. In Finland medium voltage networks are fed from the 110 kV (HV) subtransmission system. Distribution network companies operate MV (20 kV) and LV (0.4 kV) networks which may be built as looped but are operated radially. In Finland MV networks are operated neutral isolated or coil earthed. HV and MV networks provide supply to large customers but the vast majority of customers are connected to LV networks. In rural areas MV and LV networks consist of overhead lines while in urban areas underground cables are typical.

TABLE I. Input data of the case studies.

Distribution company	R1	R2	R3	R4	U1	U2
Number of substations	32	8	8	4	9	4
Number of feeders	173	43	76	26	100	50
Total feeder length (km)	51.7	32.6	16.8	27.8	6.3	11.1
Main feeder length (km)	20.0	20.7	13.5	19.7	5.0	9.0
Number of laterals / feeder	2.8	14.0	1.4	2.0	1.0	1.1
Feeder resistance (Ω/km)	0.50	0.54	0.29	0.40	0.17	0.18
Feeder reactance (Ω/km)	0.40	0.34	0.25	0.38	0.12	0.12
Fault frequency (1/km/a)	0.034	0.038	0.065	0.083	0.044	0.045

In a case of rural companies the source impedance was assumed to be 1.6 Ω (equals to 1.4 kA short circuit at 110 kV level) and urban companies 0.3 Ω (equals to 7.3 kA at 110 kV level). Rural companies were assumed to have a 20 MVA transformer at HV/MV substation and urban companies a 40 MVA transformer. The fault frequency in Table I has been determined from data of permanent faults. In the calculations it was assumed that fault frequency is constant along the total feeder length. Only three phase short circuits having fault impedance of 0 ohms were calculated. Two phase short circuits, earth faults and non-permanent faults were taken into account by modifying the sag distribution caused by three phase short circuits [4]. The calculated non-cumulative sag distributions are presented in Fig. 2 – Fig. 7.

The results are highly dependent on network characteristics. Mainly because of the short total feeder length urban customers seem to experience less sags than rural customers. In addition urban sag distribution lacks the shallowest voltage sags. Urban sags are severe but rare compared to rural ones.

In a case of rural company 2 the impact of a larger number of branches can be seen. The branches increase the total feeder length. In addition the location of branches can have a substantial effect on sag distribution especially if they are located close to the PCC.

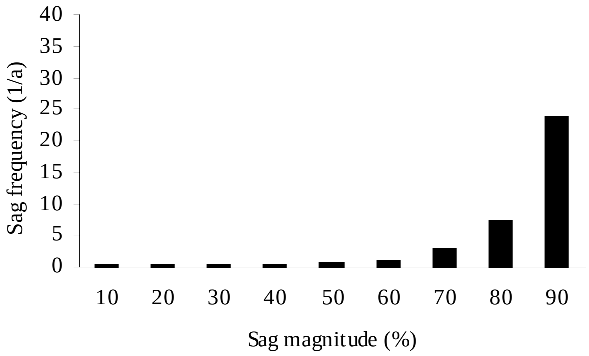

Fig. 2. Sag frequency of rural company R1.

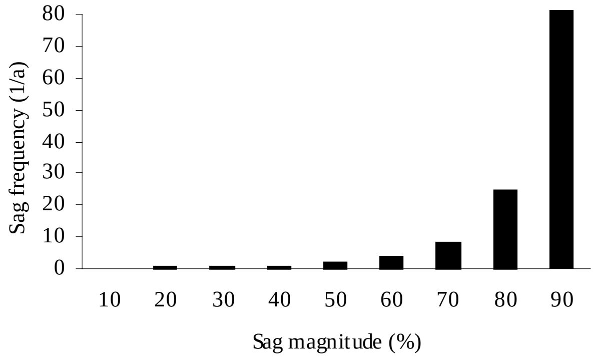

Fig. 3. Sag frequency of rural company R2.

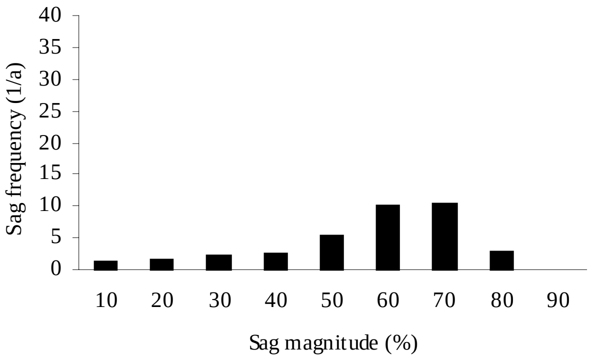

Fig. 4. Sag frequency of rural company R3.

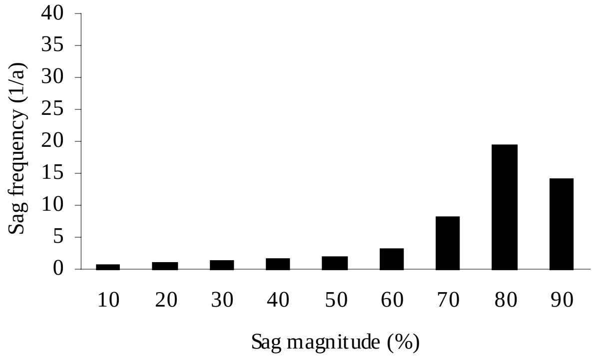

Fig. 5. Sag frequency of rural company R4.

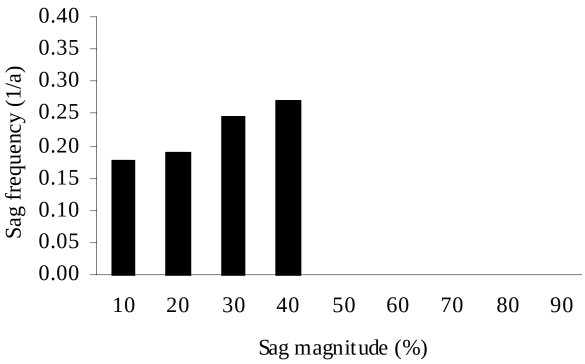

Fig. 6. Sag frequency of urban company U1.

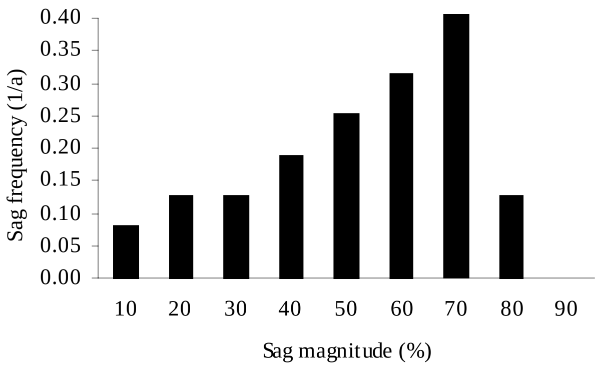

Fig. 7. Sag frequency of urban company U2.

IV. DISTRIBUTION DESIGN AND VOLTAGE SAGS

Traditionally the network information systems (AM/FM-GIS) used in power distribution companies do not include tools for sag analysis although a lot of data is available for such calculation. To be able to serve the increasing number of sag sensitive customers distribution companies should have tools also for voltage sag analysis. While voltage sag analysis may suggest network solutions that are not acceptable from another point of view, voltage sag analysis must not be kept as a separate analysis but included as one tool among the other network planning and operation tools, e.g. load flow, fault current and reliability analysis.

A. An investment to improve reliability

Traditionally one aim of network design and operation is to minimise the impact of interruptions to customers. Underground cable networks seem to be superior compared to overhead line networks because of their lower fault frequency. When having sag sensitive customers in mixed underground cable and overhead line networks the way of thinking is no more this straightforward. The aim of decreasing interruptions and voltage sags can bring competing aspects to network design.

Underground cable networks have compared to overhead line networks

- lower fault frequency. Less faults mean less interruptions and voltage sags.
- larger cross sections. Larger cross sections mean lower remaining voltage during a sag. In addition the area of vulnerability is wider in underground cable networks.

Three cases of mixed networks were analysed:

A. half of the overhead line main feeder (the half closer to the PCC) is replaced by underground cable

B. the whole overhead line main feeder is replaced by an underground cable

C. all the overhead line laterals are replaced by underground cables.

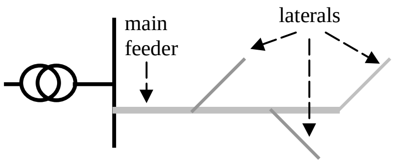

Fig. 8. MV feeder.

It was assumed that the fault frequency of underground cable networks is 10% of the fault frequency of overhead line networks.

The results are presented compared to results of rural companies performed in previous Chapter III. The percentual changes in interruptions and sag frequencies U_{sag}<50% of study cases A, B and C are presented in Table II. Despite the improvement of decreased number of interruptions the sag frequency may be increased. Especially the replacement of overhead lines with underground cables in the neighbourhood of PCC and having overhead line network downstream the cable network can have unexpected effects on sag frequency.

TABLE II. Percentual changes in interruptions and sag frequencies in study cases A, B and C.

	A		B		C	
	Inter-ruptions	Usag <50%	Inter-ruptions	Usag <50%	Inter-ruptions	Usag <50%
R 1	-7%	+68%	-13%	+21%	-77%	0%
R 2	-3%	+181%	-6%	+168%	-84%	-32%
R 3	-23%	+31%	-45%	-18%	-45%	-12%
R 4	-19%	+43%	-39%	-29%	-51%	0%

The sag frequency results are also presented in Fig. 9. If the ratio of frequencies exceeds the horizontal line 1.0 the mixed network has a higher sag frequency than the base case of purely overhead line networks.

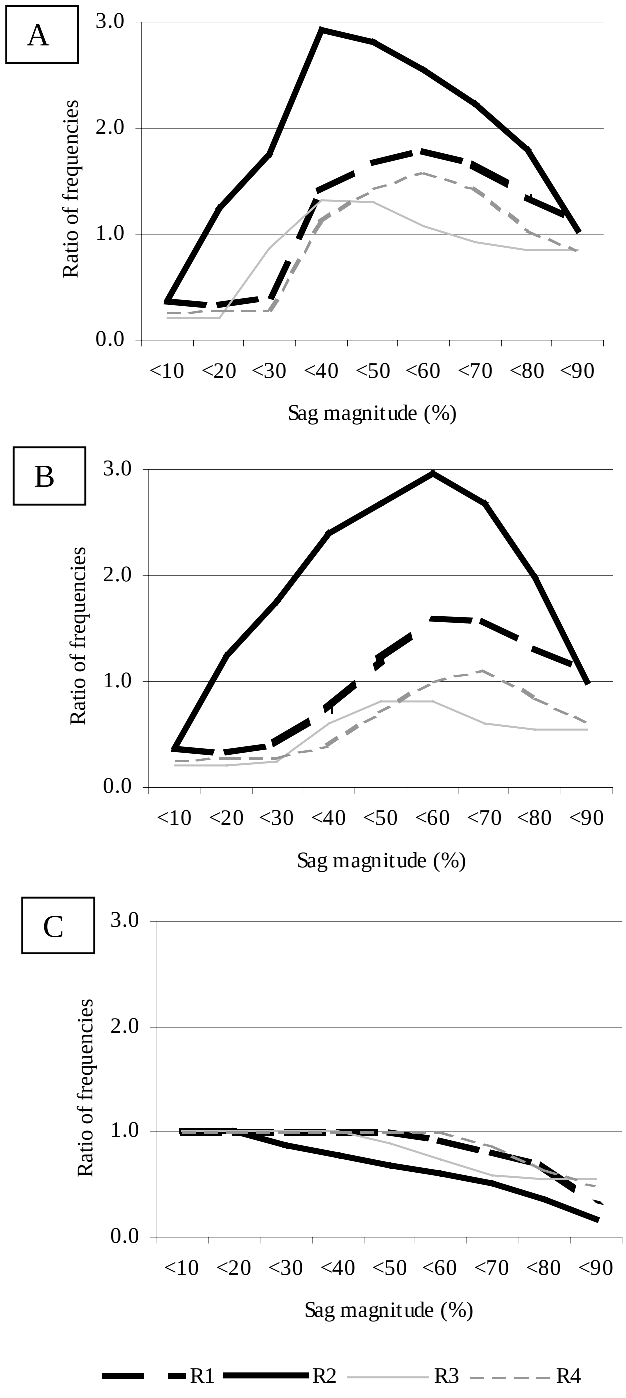

Fig. 9. The ratio of cumulative sag frequencies for mixed overhead line and underground cable networks versus purely overhead line networks.

In a case of main feeder of an underground cable (Fig. 9: A, B) the sag frequency of the most severe sags is decreased because the lower fault frequency of underground cable. A special attention should be paid to a result that the area of vulnerability of sags $30\%<U_{sag}<70\%$ is remarkably increased in case A. This is because the smaller feeder impedance of underground cable networks brings the rest of overhead line networks (with its higher fault frequency) electrically closer to the PCC. This result is no more valid in a case where only overhead line laterals (case C) are replaced by underground cables.

Underground cable networks would be preferred compared to overhead line networks because of their lower fault frequency. The study cases revealed that mixed networks of underground cables and overhead lines on the same feeder need a separate voltage sag analysis. The area of vulnerability of sags $30\%<U_{sag}<70\%$ was remarkably wide in a case of a mixed network where the half of the main feeder closer to the PCC was an underground cable and rest of the feeder was overhead lines. The increase in sag frequency was unpredictably high.

B. Voltage sag analysis included in network design and operation

Power distribution companies have traditionally carried out power flow and fault current calculations for their distribution network for monitoring and planning purposes. The network is controlled and operated as a complete system. Network information systems (AM/FM-GIS) and different distribution management systems (DMS) are the most common software platforms used for completing the task. Network information systems have much data available also for voltage sag calculations and thus the voltage sag calculation and voltage sag evaluation tools would be among the other calculation and analysis programs in network information systems (Fig. 10).

To be able to compare the possible competing aspects of power quality in power distribution planning and operation also the economic impact of voltage sags should be determined [5]. Voltage sag analysis included in network information system should have procedures to

- assess voltage sag distribution for each supply point
- locate the sag sensitive customers and determine their critical voltage sags
- determine the economic damage caused by voltage sags for each customer or customer type

The calculation procedure of voltage sag distribution is straightforward and all the data is basically available in the network information systems in use. One cause of inaccuracy in these calculations is the input data of fault frequency, however. Traditionally fault frequency is determined from data of permanent faults. This data should be more detailed to involve also information of shares of different fault types including also non-permanent faults.

To determine one representative critical voltage sag value for each customer e.g. a model can be created which takes into account the combination of sag sensitive device the customer or customer type has. Further the model creates one representative sag value for each customer type and takes into account also the probability whether the customer is disturbed or not [6].

The voltage sag analysis needs also data of the cost of voltage sags. This is not a simple task. In addition the value of the sag oriented inconvenience or disruption for the customer is a most subjective matter [4], [7].

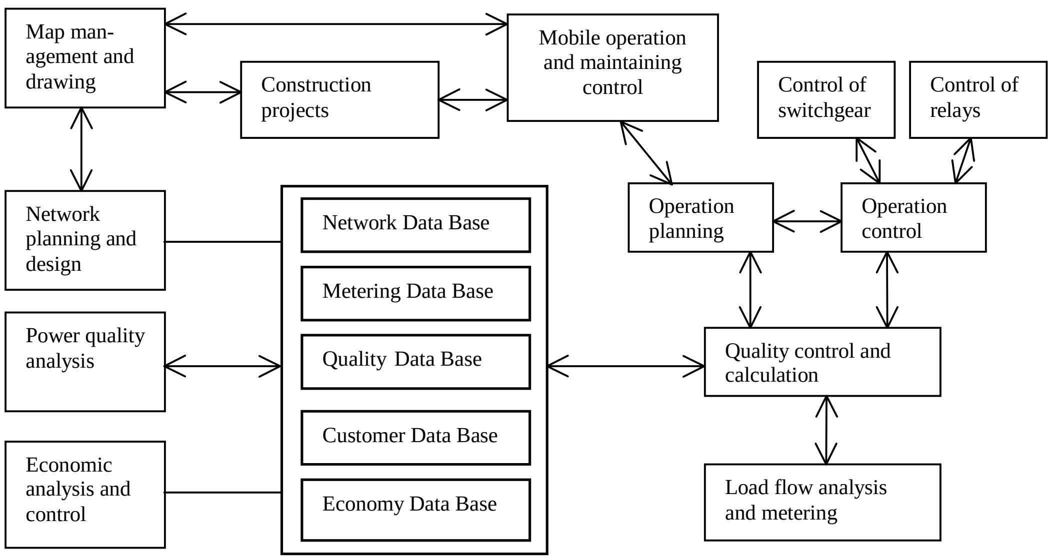

Fig. 10. The elements of distribution network information and design systems including the connections of power quality tools.

The result of voltage sag analysis offers the economic impact of sags to be included into a technical and economic optimisation problem of distribution network design. In that the long term total costs including costs of investments, losses, outages and poor power quality is minimised within relevant constraints.

V. CONCLUSIONS

Voltage sag distributions were calculated for four rural and two urban Finnish distribution companies. Urban customers seem to experience less sags compared to rural customers the main reason being the shorter total feeder length of urban underground cable networks. Urban sag distributions lack the shallowest less severe sags, on the opposite in rural systems the share of the shallowest sags is remarkably higher than the share of the most severe sags. In addition in rural networks the feeder length may be so long that part of it can be neglected in sag analysis. As well in urban as rural systems the feeder branches can have a remarkable effect on voltage sag distribution.

It was shown that while the replacement of an overhead line with an underground cable means typically a decrease of interruptions it might in mixed networks mean an increase in sag frequency. Especially investments in the neighbourhood of PCC need a separate sag analysis to be performed to avoid unexpected impacts to sag sensitive customers.

Voltage sag analysis should be linked as a part of comprehensive network design. Almost all the data needed in sag analysis is already available in network and customer data base. The sag analysis needs further research of different fault types and more understanding about the sag sensitive equipment and the economic impact of voltage sags.

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VII. BIOGRAPHIES

Pirjo Heine was born in Rauma on August 29, 1963. She received the Master of Science degree from Tampere University of Technology in 1987. Now she is a researcher at the Power Systems Laboratory of Helsinki University of Technology. Her main interests are in power quality issues of distribution networks.

Matti Lehtonen (1959) has been with VTT Energy, Espoo, Finland since 1987 and since 1999 with Helsinki University of Technology. Matti Lehtonen received his Master’s and Licenciate degrees from Helsinki University of Technology, in 1984 and 1989 respectively, and the Doctor of Technology degree from Tampere University of Technology in 1992. The main activities of Dr. Lehtonen include earth fault problems, harmonic related issues and applications of information technology in distribution automation and energy management.

Erkki Lakervi was born in Helsinki on March 26, 1945. He received the Master of Science degree from Helsinki University of Technology in 1969 and the Dr.Tech. degree from Tampere University of Technology in 1984. In the 1970’s he headed the general planning and hydro generation departments in two Finnish utilities. From 1976 to 1997 he was an associate professor and professor at the Power Engineering Group of Tampere University of Technology. He is now professor at Power Systems Laboratory of Helsinki University of Technology.