PUBLICATION 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.

Economic Analysis of Implementing Novel Power Distribution Automation

E. Antila
ABB Oy
Vaasa, Finland
erkki.antila@fi.abb.fi

P. Heine, and M. Lehtonen
Helsinki University of Technology
Espoo, Finland
pirjo.heine@hut.fi, matti.lehtonen@hut.fi

***Abstract*— Three solutions for novel distribution automation implemented in medium voltage networks were developed as a theoretical study. The distribution automation studied included intelligent local automation arrangements also useable for ring-type networks. The profitability of the new technique was evaluated by comparing the costs of the automation investments to the savings obtained in the economic impact of interruptions and voltage sags calculated for four different networks. The results showed that the new technique offers promising possibilities in limiting the effects of interruptions and voltage sags. The degree of automation must be adapted to each network construction. The selection of the adequate degree of automation assures the operational capability of the network company.**

Distribution automation, network automation, voltage interruption, voltage drop, voltage sag, series connected power conditioner

I. INTRODUCTION

In general, medium voltage (MV) power distribution networks are operated radially, with different levels of distribution automation. Investment in distribution automation is a technical and an economic optimisation issue to be considered in distribution network design. The purpose is to minimise long term total costs including costs of investments, losses, outages and poor power quality within relevant constraints.

Power quality is of increased concern. Previously, long interruptions have been of major interest but nowadays the focus is on shorter interruptions. From the customer point of view, short interruptions and voltage sags affect customer equipment in the same way. Distribution automation can be used to control the influence of interruptions and voltage sags. Novel solutions of distribution automation include, for example, modern, intelligent systems and equipment for fault isolation and optimised operation and control of the network.

This paper studies the development of distribution automation in order to minimise the economic and qualitative effects caused by outages and voltage sags in power systems. For this purpose, automation solutions are developed, in which both the return on investment and feasibility of the solutions in certain networks are studied and discussed. The economical benefits of similar solutions have not previously been surveyed and assessed for a whole medium-sized distribution network. The aim of this paper is to demonstrate the profitability and benefits of a comprehensive automation solution.

II. VOLTAGE SAGS AND INTERRUPTIONS

From the customers' point of view interruptions and voltage sags have an equally harmful influence on the operation of equipment and processes. An interruption is defined as the complete loss of voltage (< 0.1 p.u) and a voltage sag as a voltage drop to between 0.1 and 0.9 p.u. in rms voltage [1]. Voltage sags can be characterised by magnitude, duration, and number [2]. The lower the sag magnitude and/or the longer the sag duration, the higher is the probability of misoperation of the customer's equipment.

In radially operated MV networks having circuit breakers only at the substation, a customer experiences sags caused by faults in the neighbouring MV feeders, while customers supplied by the faulted feeder will face an interruption. In a construction with downstream circuit breakers along the feeders, customers will also experience sags caused by faults in the neighbouring feeders. In this situation, depending on the relative location of the customer and the fault, customers may also experience interruptions and sags caused by faults occurring in the same feeder as the customers themselves.

III. NOVEL AUTOMATION

Different solution models of varying effectiveness of automation can be adopted for automatic fault clearance. In this paper, the alternatives have been limited to three solutions on different automation levels. The first one is based on the traditional centralised automation model (Solution A, Fig. 1), in which all operational functions are centralised in the remote control system. The second model is called the total automation model (Solution B, Fig. 1), in which measurements and local functional intelligence are utilised, for instance, by performing local high-speed auto-reclosing on overhead lines. The third solution, with the most effective degree of automation (Solution C, Fig. 1), is based on fast and reliable protection functions enabling looped operation of the network. In this protection model, local station high-speed auto-reclosing is performed also in rural networks.

The centralised automation solution is based on established technology, where network disconnectors are supervised and controlled by the remote control system. The disconnector control is synchronised with the substation circuit breaker to allow disconnector control only when the substation circuit breaker is open.

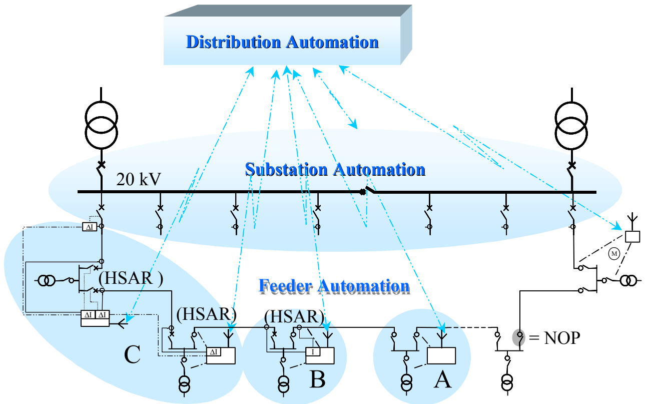

Fig. 1. Network model showing automation solution alternatives (HSAR – High-Speed Auto-Reclosing, NOP – Normal Open Point).

In the centralised automation model, intelligent operations are concentrated in central control room systems, such as the network control and network information systems. This being the case, faults are, in general, easily and effectively managed, because the control centre commonly incorporates a fairly high data processing capacity.

The total automation solution is a combination of centralised and local automation. Centralised intelligence has also been distributed to local terminal devices enabling faulty line sections to be locally disconnected from the network, provided sufficient information is available.

Contrary to the centralised model, the total automation model is complemented with local measurements. The terminal device is programmable, a feature which is utilised in the local automation solution. It checks, for instance, the sufficiency of the current breaking capability of the disconnector in a line fault. Further, the local processing power supported by the information system of the control centre enables fast action in different fault situations.

In this context, the protection model is studied solely for the ring networks. The protection model for the ring network is the most powerful solution from the fault clearance point of view. It must, however, rely on the remote control functions exposed in the centralised model. These are required for maintenance and operational functions. The power of the solution is based on pilot protection.

In this paper, the pilot protection is formed between two automation stations equipped with directional relays located at the ends of the line section (Fig. 2). Depending on the selected operating principle, the relays interchange tripping and blocking signals. Permissive comparison protection systems have to be provided with back-up protection, in case the communication between stations fails. On the other hand, comparison protection based on blockings needs a fixed delay to give the blocking signal time to arrive. Due to the required margin of the blocking signal, this is the slowest protection model.

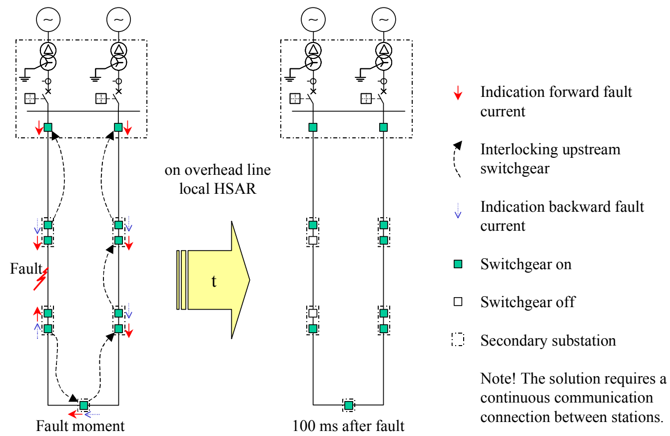

Fig. 2. The automation solution by the protection model.

Further, the communication protocol must comply with the speed requirements of the protection. As an example, measurements suggest that a response time of 100 ms can be guaranteed when the LON protocol is used.

In practice, faults can be effectively and reliably isolated, but with no better accuracy than the distance between disconnectors. Further, the solution can conveniently be complemented with a fault location system based on distance calculation.

IV. STUDY CASE

The three distribution automation concepts presented in Paragraph III are applied to four different MV distribution networks: Rural1 (R1), Rural2 (R2), Urban1 (U1), Urban2 (U2). The costs of interruptions and voltage sags ($U_{sag} < 50\%$) and the automation investments are calculated. Further these costs are compared to a simplified solution (model 0) where no remote control facilities are in use. Two of the networks represent typical rural MV overhead line networks with one transformer at the HV/MV substations. The transformer supplies on an average five feeders with a typical length of some tens of kilometres. Auto-reclosing is in use for the protection. The other two networks represent typical urban networks with substations provided with two HV/MV transformers supplying about ten MV underground cable feeders typically only some kilometres in length. Auto-reclosing is not used since practically all faults are permanent.

Protection zones for distribution automation purposes are shown in Fig. 3 and in Fig. 4. The analysis takes into account fault data according to [3]. In interruptions, the customers experience an interruption of either a repair time or a switching time (Table I). For solution 0, the repair time is R1 2.62 h, R2 3.5 h, U1 0.58 h, U2 1.37 h and for the other solutions half of these values. The switching time for solution 0 is half of the values presented above, for the other solutions 1 minute. Customers are distributed equally along the feeder length. The customer data applied is presented in Table I and Table II.

Table I

MV NETWORK INPUT DATA OF THE CASE STUDIES [4].

Variable	Rural 1	Rural 2	Urban 1	Urban 2
NOTpF	45	24	10	20
NOCpT	8	13	112	85
MPpC	1.49	3.12	3.00	2.14

NOTpF = Average number of transformers per feeder
NOCpT = Average number of customers per transformer
MPpC = Mean power per customer (kW)

Table II

DISTRIBUTION OF POWER BETWEEN DIFFERENT CUSTOMER GROUPS [4].

	Rural 1	Rural 2	Urban 1	Urban 2
Domestic (%)	36	37	42	48
Agricultural (%)	20	24	0	0
Industrial (%)	12	12	21	11
Commercial (%)	10	15	28	30
Public (%)	22	12	9	11

Different customer groups estimate the inconvenience caused by voltage sags and interruptions in a different way. In this study, the following costs of voltage sags and interruptions for different customer groups were applied (Table III) [3]:

Table III

VALUE USED FOR A SINGLE VOLTAGE SAG AND INTERRUPTED P.U. DEMAND AND ENERGY IN EACH CUSTOMER CLASS [3], [5].

Customer category	Cost per sag (€)	Cost for interruption	
		for demand (€/kW)	for energy (€/kWh)
Domestic	1	0	1.4
Agricultural	1	0	11.2
Industrial	1 060	4.4	18.6
Commercial	170	4.0	22.2
Public	130	1.2	7.4

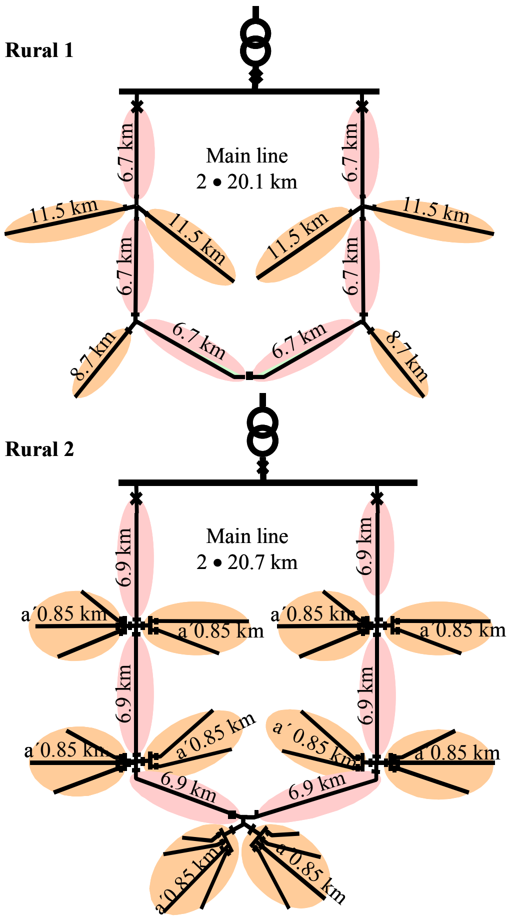

Fig. 3. Protection zones and models of the rural networks.

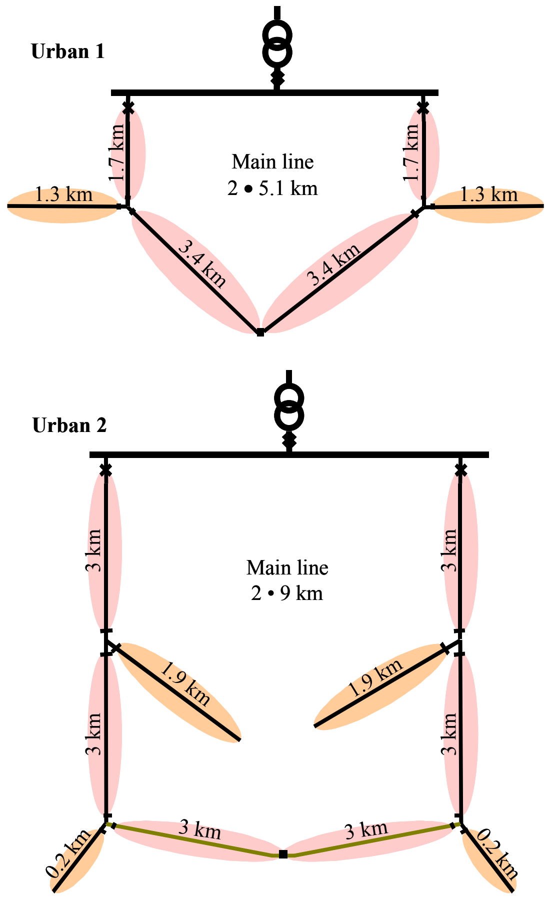

Fig. 4. Protection zones and models of urban networks.

V. ANALYSIS OF ECONOMIC SOLUTION

For each operation solution the average costs of interruptions and sags are calculated for two radial feeders or one ring feeder formed by two radial feeders. In these study cases, it is assumed that all the remote-controlled network branches of one model are similar. In reality, however, there is a sort of mixture of different automation levels along one feeder. The investment costs of an automation concept include switching devices with sufficient breaking capacity, local automation equipment, measuring sensors, surge arresters, auxiliary supply systems, the communication system, the project-related application work and commissioning, as required by the model. In the supervision system of the control centre only the costs of the required application programs have been included.

In general, it is expected that an increased level of automation decreases interruption costs but increases investment costs. In a case where, for instance, locally operated disconnectors are replaced by remote-controlled disconnector stations, the interruption costs are assumed to decrease according to Table IV.

Table IV

ADDITIONAL BENEFIT AS PER CENT OF THE COSTS OF UNDELIVERED ENERGY WHEN CHANGING STATIONS OF REMOTE CONTROLLED DISCONNECTORS.

Number of remote controlled stations along the feeder	Additional benefit
0	0%
1	50%
2	67%
3	75%
4	80%

The results of the calculations when automating two feeders or one ring by taking into account the costs of interruptions, sags and investments are presented in Table V where the costs are annual costs of the whole investment.

Table V

COSTS OF INTERRUPTIONS, SAGS [6] INCLUDING AUTOMATION INVESTMENTS.

Model	Costs	Distribution Network (€)			
		Rural 1	**Rural 2**	**Urban 1**	**Urban 2**
Base solution (0)	Interr.	75 453	109 292	14 319	48 484
	Sags	21 642	22 845	1 999	2 661
	Total	**97 095**	**132 137**	**16 318**	**51 145**
Remote control-led (A)	Interr.	51 175	68 343	7 918	21 634
	Sags	21 642	22 845	1 999	2 661
	Total	**72 817**	**91 188**	**9 917**	**24 295**
	Invest.	**96 643**	**119 480**	**66 012**	**119 892**
Full auto-mation (B)	Interr.	21 323	40 582	5 642	17 932
	Sags	46 222	35 776	2 174	2 950
	Total	**67 545**	**76 358**	**7 816**	**20 882**
	Invest.	**191 619**	**233 905**	**105 969**	**193 901**
Protec-tion (C)	Interr.	11 574	14 815	2 756	8 490
	Sags	127 953	97 670	2 424	4 949
	Total	**139 527**	**112 485**	**5 180**	**13 439**
	Invest.	**228 736**	**288 149**	**128 301**	**232 561**

The profitability of the automation models is compared using the Internal Rate of Return (IRR) calculation method. The profitability varies with the observation periods as shown in Fig. 5. The figure also shows the change in profitability obtained when sensitivity analysis is used and the disturbance costs are varied by 50%, 100%, 150% and 200% of the current cost level.

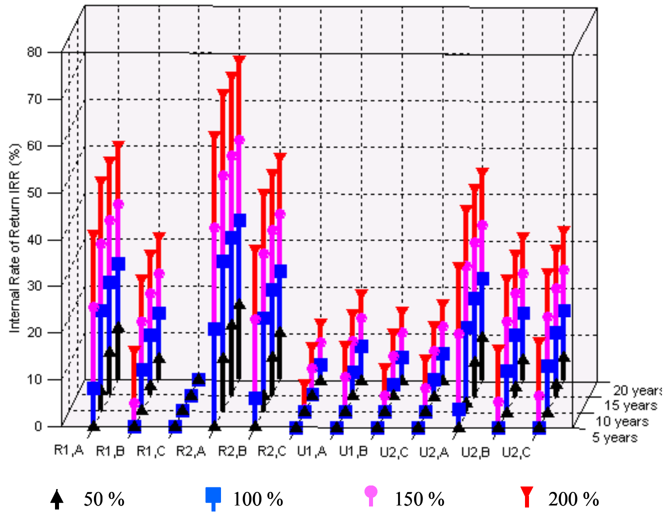

Fig. 5. Profitability of investments with estimated disturbance costs (R Rural, U Urban).

In a ten-year observation period, the profitability threshold, based on an internal interest rate of roughly 10%, is reached or exceeded in a rural network automation project, except for the solution according to the protection model which never reaches profitability. In simple urban networks, automation is not either particularly beneficial. In large urban networks, however, all of the model solutions reach the 10% threshold value.

Voltage sags cause inconvenience only for some sag-sensitive customers. It can be seen in Fig. 6 that most of the customers do not experience any harmful influence caused by voltage sags, at all. On the opposite, the influence can have an extremely high value for some customers. However, these special customers typically are able to invest in solutions limiting this negative effect. Custom power devices, for example, series-connected power conditioners, offer promising means to serve sag-sensitive customers.

The different automation solutions presented above can be recalculated in a case where series-connected power conditioners are added to the network to limit the inconvenience caused by voltage sags. It is assumed that 10% of the customers experience 90% of the negative effects caused by voltage sags. This additional benefit is shown in Table VI

Table VI

ADDITIONAL BENEFIT IN LIMITING THE EFFECT OF VOLTAGE SAGS WHEN USING CUSTOM POWER DEVICES.

Number of custom power devices per feeder	Additional benefit	
	rural	urban
1	22.5%	45.0%
2	45.0%	90.0%
3	67.5%	
4	90.0%	

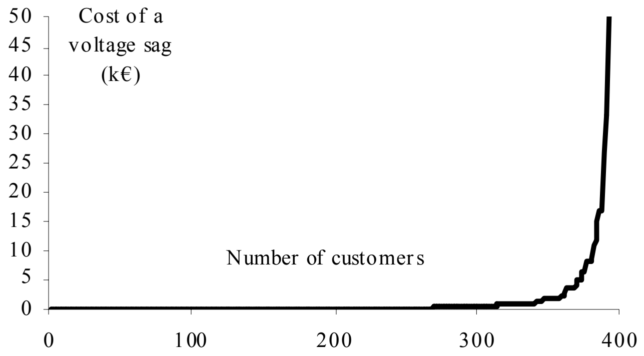

Fig. 6. Inconvenience caused by voltage sags [5].

The installation of a custom power device is an additional investment. Here, it is assumed that the cost of one series-connected power conditioner is 30 000 Euro, which corresponds to a typical load of 200 kW in a LV (low voltage) network. The calculated profitability of the investments when two custom power devices are used during a ten-year observation period can be found in Table VII. The installation of this kind of custom power equipment seems to be a considerable improvement.

Table VII

PROFITABILITY OF INVESTMENTS.

	No custom power (Fig. 5)	Custom power (two device)
R1,A	17 %	33 %
R1,B	15 %	23 %
R1,C	0 %	0 %
R2,A	26 %	42 %
R2,B	21 %	28 %
R2,C	13 %	14 %
U1,A	0 %	4 %
U1,B	0 %	0 %
U1,C	0 %	1 %
U2,A	10 %	21 %
U2,B	5 %	11 %
U2,C	7 %	13 %

In all these cases of study, it was assumed that all the remote-controlled network branches in the network were similar in the different models. In real life, however, the network is more likely to include a mixture of the automation models presented in this paper.

VI. CONCLUSIONS

Three solutions for novel distribution automation implemented in four different medium voltage networks were developed in a theoretical study. The networks represented typical rural and urban networks. New distribution automation means investment in the network but, on the other hand, it offers promising opportunities to operate the network both in normal situations and in fault situations. In this paper, the investments were compared to the savings obtained through reduced inconvenience of interruptions and voltage sags.

The profitability calculations are based on the Internal Rate of Return method. The results suggest that the automation of rural networks is a reasonably profitable affair in a time frame of over ten years, except for the ring network solution of the protection model. In limited urban cable networks, distribution interruptions and voltage sags alone do not justify automation. On the other hand, the automation of urban networks is profitable in large and versatile distribution networks.

In this paper, also a study of installing custom power was performed. Voltage sags represented considerable inconvenience in the calculated examples. Most of the customers do not experience voltage sags as negative at all, but on the other hand, some special customers experience voltage sags as very harmful. The study of the cases with custom power devices showed that this new technology is a promising alternative. However, different mixed network-specific solutions of the models presented in this paper are probably the most interesting solutions.

According to the study, automation is an effective way to improve the reliability of a distribution network and to enhance its usability. The findings clearly suggest that on a suitable level of automation it can be motivated to minimise the cost effects of distribution interruptions and voltage sags. This is also necessary because the sensitivity to interference of the customer's equipment will impose tougher quality requirements on the electricity distribution. Disturbance-free operation ensures high-quality electricity, for which the customer is prepared to pay a fair price. Because of the quality requirements the importance of cost valuation will grow. In this context, the reduced disturbance costs obtained through automation according to the sensitivity analysis of this work further improve the situation.

REFERENCES

[1] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159-1995, June 1995, 70 p.

[2] M. H. J Bollen, *Understanding power quality problems*, *Voltage sags and interruptions,* New Jersey, USA, IEEE Press, 1999, 541 p.

[3] P. Heine, P. Pohjanheimo, M. Lehtonen, and E. Lakervi, "A Method for Estimating the Frequency and Cost of Voltage Sags," *IEEE Trans. on Power Systems*, vol.17, No. 2, May 2002, pp. 290 – 296.

[4] M. Lehtonen, S. Kärkkäinen, and J. Partanen, "Kokonaisvaltainen sähkölaitosautomaatiokonsepti Suomessa (Future distribution

automation system for Finnish utilities)," VTT, Espoo, Finland, VTT Tiedotteita – Meddelanden – Research Notes 1621, 1995, 68 p. + app. 35 p.

[5] B. Lemström and M. Lehtonen, "Kostnader för elavbrott", TemaNord 1994:627, Nordisk Ministerråd, Copenhagen, 1994, 165 p. (in Swedish, summary also in English).

[6] P. Heine, and M. Lehtonen, "Costs of voltage sags and interruptions with increasing levels of automation," Helsinki University of Technology, Espoo, Tesla-report nr 65/2002, 2002, 20 p.

Analyse économique de mise en œuvre de nouvelle automatisation de distribution de puissance

***Résumé*— Trois solutions pour une nouvelle automatisation de distribution mise en œuvre dans les réseaux de tension moyenne ont été développées en tant qu'étude théorique. L'automatisation de distribution étudiée a compris des dispositions d'automatisation locale intelligente utilisables pour des réseaux de type à anneau. La rentabilité de la nouvelle technique a été évaluée en comparant les coûts des investissements d'automatisation à la réduction de l'impact économique des interruptions et chutes de tension calculées pour quatre différents réseaux. Les résultats ont indiqué que la nouvelle technique offre des possibilités promettrices pour la limitation des effets des interruptions et chutes de tension. Le degré d'automatisation doit être adapté à chaque construction de réseau. La sélection du degré d'automatisation approprié assure la capacité opérationnelle de la société du réseau.**

Automatisation de distribution, automatisation de réseau; interruption de tension; baisse de tension; conditionneur d'énergie relié en série