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Cost and benefit analysis for a distribution management system in electricity distribution networks

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Abstract

Purpose – The purpose of this paper is to examine the key outage-cost-influencing applications (fault location and network restoration, fault reporting, field crew management, and reconfiguration) of the distribution management system (DMS) and analyzes the benefits provided by them. The objective of the study is an evaluation of their influence on outage costs deriving from the adoption of automatic equipment in managing distribution systems.

Design/methodology/approach – Cost and benefit calculations in this paper are made for a typical North European rural medium-voltage network. The benefits are calculated in terms of outage costs for each of the above-presented applications and compared with the investment cost, including the annual cost of maintenance, of the DMS. The empirical results and validation of the theoretical calculations are performed by an electric utility, where the DMS benefit evaluation is taking place.

Findings – By capitalizing the applications of the DMS, it is possible to acquire considerable benefits in outage costs. It is shown that the greatest cost-based benefits are obtained from the fault location and field crew management applications. The case study further shows that the DMS can reduce the operation costs of utilities.

Research limitations/implications – The calculations are based on network expert assumptions about System Average Interruption Duration (SAIDI), carried out for a specific overhead-line network operating in a specific European rural medium-voltage environment. Sharing of utilities' *de facto* SAIDI results as a basis for calculations would decrease the need for subjective expert assumptions in the future analyses.

Practical implications – Application of the proposed framework for decision making and lessons learned can support electric utilities when planning for unbundling and strategic target-setting in the unbundled business model.

Originality/value – There are few reports available on similar actual DMS-application-based cost benefits due to the nature of private utility information that is preferably not disclosed.

Keywords Electric power transmission, Distribution systems, Cost benefit analysis

Paper type Research paper

1. Introduction

The distribution management system (DMS) and distribution automation (DA) are widely used in network companies. Over the recent years, society has become more dependent on disturbance-free distribution of electricity, and customers and owners

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increasingly place demands on the distribution network business. Customers expect good enough quality at a reasonable price of electricity while it is in the owners' interests to maximize profit within the limits of the regulation model applied (Honkapuro, 2008). Implementing DA and systems such as DMS improve the reliability of the system (Brown *et al.*, 2001; Chen and Sabir, 2001). Nowadays, many distribution companies focus on the development of data warehouses and information management, which assist in defining age and condition of the equipment; however, there is still lot to do to capitalize this information (Brown and Willis, 2006).

DA can be defined as an implementation of technology to improve the reliability, availability, and operation of the electricity distribution system (Smallwood and Wennermark, 2009), whereas the DMS is the decision-support system that helps operating personnel to operate their distribution system both in normal and emergency situations. In practice, the DMS demonstrates the real-time electrical state of the distribution network, reports the operator of possible anomalies (e.g. faults, overloading), and proposes required actions (Järventausta, 1995). The DMS includes various intelligent and advanced applications introduced in Table I (Verho, 1997).

Applications examined in this study are presented in Table I, these include fault location, fault reporting, fault restoration, field crew management, and reconfiguration. These applications were selected for study because they have a considerable influence on outage costs. Many studies have previously been published regarding the achievable benefits of DA investments; however, similar benefit analysis results have not been reported for network control system functionalities in the DMS. Hence, this study complements the literature available in the field of DMS analysis, and as the importance of network availability increases, also the need for a quantifiable cost/benefit analysis grows in order to define the real value of network reliability.

2. Task layout

Cost and benefit calculations in this paper are made for a typical North European rural medium-voltage network. The benefits are calculated in terms of outage costs for each of the above-presented applications and compared with the investment cost, including the annual cost of maintenance, of the DMS. Each application has a different influence on the System Average Interruption Duration (SAIDI), losses, the cost of labor, and investment and outage costs. Further, SAIFI will not be addressed in detail as the DMS applications do not have a considerable influence on the frequency of faults. The influences of each application on various network components are given in Table II.

Literature reviews show that there are different kinds of reported cost/benefit analyses related to savings in personnel, energy, operation and maintenance costs, and customer-related benefits (Northcote-Green and Wilson, 2007). Further, results of obtained benefits have been reported regarding fault location, isolation, and restoration

Basic monitoring	Fault management	Operations planning
Topology supervision	Event analysis and fault location	Scheduled outage planning
Network state monitoring	Fault isolation	Volt/var optimization
Field crew management	Fault restoration	Reconfiguration
	Fault reporting	
	Customer service	

Table I. Main functionalities in a DMS application

(Stacchini De Souza *et al.*, 2001; Courtney *et al.*, 2008; Roytelman and Landenberger, 2009). However, to the authors' knowledge, there have been no reports on calculation and evaluation of detailed cost/benefit analyses for specific DMS applications compared with the DMS investment cost (including annual cost of maintenance) presented in this study. Table II highlights the scope of benefits obtainable by DMS applications analyzed in the study, which will be presented in the following sections.

2.1 Introduction of DMS functionalities

Locating a fault in the network triggers the actual fault recovery actions in the fault management process (Table I). The target is to locate the fault as soon as possible so that the fault can be fast isolated from the network. Automated fault location in the DMS is based on determination of the fault current obtained from relays, generally giving the correct fault location with a +/− 100 meter accuracy. This way, it is possible to decrease SAIDI and thereby the outage costs. In a case without any advanced automation (such as microprocessor-based relays and remote-controlled disconnectors) on the network, a fault location application becomes useless (Järventausta, 1995; Verho *et al.*, 1996).

Fault restoration follows after the actual faulty section has been repaired or disconnected from the network. Network restoration performed as an activity by the network control system decreases SAIDI and outage costs, and it also has a positive effect on the cost of labor. Fault restoration function allows more optimal use of the network and thus decreases investment costs in the long term. Further, fast fault restoration reduces the amount of payable customer compensations.

The importance of fault reporting becomes vital in particular during extreme conditions (e.g. storms). In these situations, automatic fault reporting is useful afterwards especially when distribution companies are obliged to pay standard compensations to the customers (Finnish Electricity Market Act, 1995). Fault reporting is a valid DMS application that has an influence on outage costs and the cost of labor. In practice, it is possible to identify the most fault-sensitive medium-voltage feeder sections when reporting corrective works and thereby to direct redevelopment steps first to these sections. The automatic fault reporting function in the DMS generates a detailed report including the number of affected customers and the amount of non-delivered energy (Verho, 1997; Verho *et al.*, 1996). Hence, fault reporting also enhances the compensation payment process.

Field crew management becomes especially important in a specialized market environment where several actors may be simultaneously operating in the field performing corrective actions on same feeder parts. An opportunity to guide the field

Table II.
DMS application influences on various network components

Functions/costs, performance	SAIDI	Outage cost	Loss cost	Cost of labor	Investment cost	Customer compensation	Occupational safety
Fault location	+	+				+	
Fault restoration	+	+		+	+	+	
Fault reporting		+		+		+	
Field crew management	+	+		+		+	+
Reconfiguration		+	+				

crews from the control room speeds up fault repair, thus reducing SAIDI, outage costs, customer compensations, and the cost of labor. This DMS function also has a positive effect on safety at work; for the operational personnel, it is important to know where field crews are located especially for safety reasons in extreme conditions.

Network reconfiguration allows optimization of network topology and functionalities in various unplanned and planned network states (Verho, 1997). The expected outcome of a successful network reconfiguration includes both low outage and loss costs. In general, it is advisable to perform network reconfiguration a few times a year to minimize loss costs.

2.2 Factors determining the obtainable benefits

The benefits achievable by the use of the DMS functions depend largely on four factors: operational environment, network structure, level of automation, and user competence.

First, the scope of obtainable benefits depends on the operational environment of the distribution system. The benefits attainable are somewhat different in a rural environment than in an urban environment. For example, in an urban area, achieving savings in outage costs is more complex than in rural networks as an urban network typically has fewer faults and is operated as a loop without high-speed or delayed auto-reclosers or disconnectors.

Second, the physical network structure sets limitations to the obtainable DMS benefits. The actual condition and age of network components in service largely affect the reliability of the network (Ross *et al.*, 2001) and thus the scope of possible cost savings such as loss and outage costs. The amount of available network automation directly determines the possible benefits through DMS functionalities. DA including remote-controlled devices at the substation and feeder levels (e.g. circuit breakers, reclosers) and the communications infrastructure have an influence on SAIDI, SAIFI, and outage costs.

3. Cost and benefit analysis

The analysis method applied in this paper follows three steps: accumulation of the calculation data (fault levels and fault durations), selection of the benefit formula applied to calculation, and finally, analysis and evaluation of the calculated results. In this study, the formula is based on calculation of outage costs utilizing SAIFI and SAIDI values. As the outage costs are comparable with other costs in the utility and they are widely used in many countries as part of economic regulation, they will provide a generalizable approach to the application of the presented methodology.

The main outage-cost-based formulae are presented in equations (1)-(3) and equation (6) (Honkapuro, 2008). Equation (1) takes into consideration the interruption costs for one substation (MV/LV). Hence, the total number and duration of interruptions for one feeder is the sum of all distribution substations connected to feeder:

$$\mathrm{IC}_{\mathrm{unan,an}} = \sum_{i=0}^{I} \sum_{j=0}^{J} \mathrm{CA}_{i,j} \overline{P}_{i,j} \left(t_i A_{j,\mathrm{kWh}} + B_{j,\mathrm{kW}} \right) \quad (1)$$

where $\mathrm{IC}_{\mathrm{unan,an}}$ are the interruption costs of the unannounced and announced interruptions, $\mathrm{CA}_{i,j}$ is the number of customers in the customer group j affected by the outage i, $\overline{P}_{i,j}$ is the average interruption power (kW) of the customer of the customer group j caused by the interruption i, t_i is the interruption time of the outage i, $A_{j,\mathrm{kWh}}$ is the outage cost parameter A (€/kWh) for the customer group j for unannounced and announced outages, $B_{j,\mathrm{kW}}$ is the outage parameter B (€/kW) for the customer group j for unannounced and announced outages, I is the number of interruptions during a certain time period, and J is the number of different customer groups.

Interruption costs for short interruptions can be calculated as shown in equations (2)-(3):

$$\mathrm{IC}_{\mathrm{High-speedAR}} = \sum_{i=0}^{I}\sum_{j=0}^{J} CA_{i,j}\overline{P}_{i,j}A_{j,\mathrm{High-speedAR}} \tag{2}$$

where $\mathrm{IC}_{\text{High-speedAR}}$ are the interruption costs of the high-speed auto-reclosings, and $A_{j,\mathrm{High-speedAR}_i}$ is the outage cost parameter A (€/kW) for the customer group for high-speed auto-reclosings:

$$\mathrm{IC}_{\mathrm{delayedAR}} = \sum_{i=0}^{I}\sum_{j=0}^{J} \mathrm{CA}_{i,j}\overline{P}_{i,j}A_{j,\mathrm{delayedAR}} \tag{3}$$

where $\mathrm{IC}_{\mathrm{delayedAR}}$ are the interruption costs of the delayed auto-reclosings and $A_{j,\mathrm{delayedAR}}$ is the outage cost parameter A (€/kW) for the customer group j for the delayed auto-reclosings.

SAIFI is the average number of interruptions per utility customer during the period of analysis. An equation for SAIFI is given by equation (4) (Verho *et al.*, 1996):

$$\mathrm{SAIFI} = \frac{\sum \lambda_i N_i}{N_i} \tag{4}$$

where λ_i is the failure rate and N_i is the number of customers at load point i.

SAIDI is the average duration of all interruptions per utility customer. The definition of the SAIDI is given in equation (5) (Verho *et al.*, 1996):

$$\mathrm{SAIDI} = \frac{\sum U_i N_i}{N_i} \tag{5}$$

where U_i is the annual outage time and N_i is the number of customers at load point i.

The calculation method used to determine the benefits of reconfiguration is given by equation (6):

$$C_{\mathrm{Benefit}} = W \times \Delta h \times h_{\mathrm{cost}} \tag{6}$$

where W is the annual energy consumption and h is the change (percent) in losses in the annual energy consumption (MWh), and h_{cost} is the cost (€/MWh) of losses.

For calculation of the annual investment cost of the DMS, equation (7) is given:

$$\varepsilon = \frac{p/100}{1 - 1/(1 + p/100)^t} \times C_{\mathrm{inv}} \tag{7}$$

where p is the interest rate, t is the lifetime, and C_{inv} is the investment cost.

For calculation of the present value of fault-reporting-related cost benefits over 40 years, equation (8) is given:

$$C_{\mathrm{BenefitPV}} = \frac{1}{1 + (p + 100)^{t}} \times C_{i} \quad (8)$$

where $C_{\mathrm{BenefitPV}}$ is the present value cost benefit per feeder, p is the interest rate, t is the year of feeder renovation, and C_i is the cost of interruption for the feeder part.

4. Initial data and results of the calculations

Initial data used in the following benefit calculations contain:

- specific network and cost parameters presented in Tables III and IV received from the Finnish Energy Market Authority and the case electric utility Suur-Savon Sähkö Oy; and
- certain empirical average presumptions given by the network experts interviewed.

These basic facts include the following:

- the medium-voltage network is a neutral-isolated system;
- short-circuit faults can be located by the DMS application;
- because of the neutral-isolated system, earth faults cannot be located by the DMS application by calculation of fault currents; and
- two-third of all faults in the distribution network are earth faults.

The case medium-voltage network is represented by 5 MV feeders, each of them 40 km long. The mean power of the feeders is 800 kW and the average failure rate is 7 pcs/100 km, a. The key outage parameters used in calculation of the cost of interruption are 1.34 €/kW and 12.85 €/kWh presented in italicface in Table IV. For the case network, SAIDI is 90 min under basic conditions, which can be considered typical for a network of this kind.

Default primary substation	
Number of feeders (pcs/substation)	5
Average length of feeder (km)	40
Failure rate (pcs/100 km, a)	7
High-speed automatic reclosings (pcs/100 km, a)	50
Delayed automatic reclosings (pcs/100 km. a)	20
Mean power (kW)	800
Peak load (kW)	2,000
Annual energy losses (percent)	3
Peak operating time of the load (h, a)	3,000
Price of loss energy (€/MWh)	45
Interest rate (percent)	5
Investment cost (k€) of DMS	160
Lifetime of DMS(a)	5
Cost of maintenance, a/investment cost of DMS	10-15 percent

Sources: Lohjala (2008); Finnish Energy Market Authority (2008)

Table III. Initial data used in the calculations

Table IV.
Finnish outage cost parameters for customer groups

Customer type	Unannounced interruption €/kW	Unannounced interruption €/kWh	Announced interruption €/kW	Announced interruption €/kWh	High-speed auto-reclosing €/kW	Delayed auto-reclosing €/kW
Household	0.36	4.29	0.19	2.21	0.11	0.48
Agriculture	0.45	9.38	0.23	4.80	0.20	0.62
Industry	3.52	24.45	1.38	11.5	2.19	2.87
Public consumption	1.89	15.08	1.33	7.35	1.49	2.34
Service	2.65	29.89	0.22	22.8	1.31	2.44
Total (weighted value)	*1.34*	*12.85*	*0.49*	*7.52*	*0.75*	*1.33*

Sources: Lohjala (2008); Finnish Market Authority (2009)

Table IV presents the Finnish outage cost parameters, where the average costs €/kW and €/kWh for interruptions and reclosings for general customer groups are obtained from the Finnish Energy Market Authority. Then, utilities can, go on their specific customer group distribution, calculate the weighted averages for their specific networks. The customer distribution in the specific network area of the case electric utilities the following: households 48 percent, agriculture 12 percent, industry 15 percent, and public consumption and services 15 percent. Thus, by multiplying each outage cost parameter by the correct customer group percentage, we obtain a weighted total value that will be used in the calculations (presented with italicface in Table IV).

Further, generalizable network assumptions used in the calculations include the following statements based on expert interviews:

- By adding a remote-controlled disconnector to the case MV feeder, a 15 min saving can be achieved in the original SAIDI of 90 min, that is, the new SAIDI equals 75 min.
- By using the fault location functionality for instance for short-circuit faults, a 15 min saving can be achieved in SAIDI, that is, the new SAIDI equals 60 min. Remote-controlled disconnectors are assumed to be in service in the network.
- Use of field crew management in the DMS when possible: by using the field crew management functionality for instance for short-circuit faults, a further 10 min saving can be achieved in SAIDI, that is, the new SAIDI equals 50 min.
- Use of network reconfiguration: by optimizing the network, the annual energy loss of 3 percent (Table III) can be cut by 10 percent, that is, the new annual energy loss equals 2.7 percent.
- Use of fault reporting: by the fault reporting function, re-development actions can be directed first to the feeder parts with the highest failure rate.

The network assumptions for the different DMS application cases in the calculations are shown in Figure 1.

4.1 Fault location and restoration

The target of fault location is to locate the fault as soon as possible to isolate it swiftly from the network. Fault location in the DMS can be used only for the short-circuit faults representing a third of all faults in the case analysis. A remote-controlled disconnector is also positioned on the network so that SAIDI will be 75 min. It is further assumed that in an optimal situation, fault location decreases SAIDI by 15 min (Figure 1), which is based on the fact that fault location speeds up switching off the faulted line section.

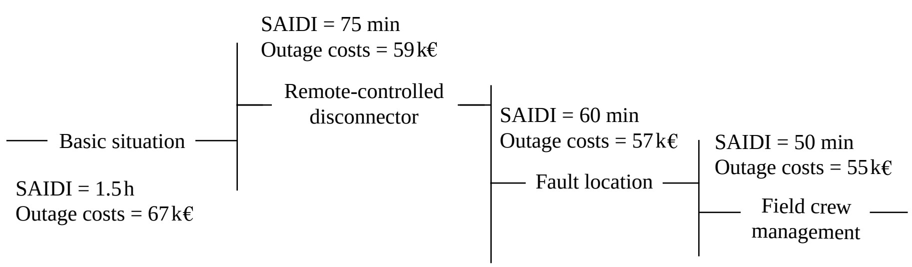

Figure 1.
Influences of DA and DMS applications on outage costs

By applying equations (1)-(3), the initial data in Tables III and IV, and the new SAIDI assumptions of 75 (no fault location) and 60 min (fault location), the outage cost is first calculated for the basic situation without fault location, after which similar outage cost calculation is performed in the case when fault location in the DMS is used. By fault calculation, only one-third of all faults can be located, and therefore the calculations are made with the lower SAIDI of 60 min. It follows that the benefit of fault location per feeder is:

$$C_{\text{benefit,feeder}} = C_{i,\text{nofl}} - C_{i,\text{flshortcircuits}} \tag{9}$$

where $C_{i,\text{nofl}}$ is the cost of interruption with no fault location and $C_{i,\text{ flshortcircuits}}$ is the cost of interruption with fault location of short circuits.

It follows that:

$$\begin{aligned} C_{\text{benefit,feeder}} &= \frac{1}{3}\times((800\,\text{kW}\times 0.07\times 40\,\text{km})\times(1.25\,\text{h}\times 12.85€/\text{kWh}+1.34€/\text{kW})) \\ &\quad -\frac{1}{3}\times((800\,\text{kW}\times 0.07\times 40\,\text{km})\times(1.0\,\text{h}\times 12.85€/\text{kWh}+1.34€/\text{kW})) \\ &\approx 2.5\,\text{k€/feeder, a} \end{aligned}$$

Finally, in the case network with five feeders per substation, the total annual benefit is approximately 12.5 k€.

The benefit of network restoration by the DMS planning application is shown as a positive effect on the cost of labor as the network can be automatically restored from the control room to the state prior to the occurrence of the fault.

4.2 Field crew management

In the benefit calculation of the field crew management application in the DMS, we assume that the application can be used only for the short-circuit faults, which represent a third of all faults. Again, earth faults cannot be located by the DMS fault location application, which means that the comparative network situation (Figure 1) with the use of remote-controlled disconnectors and SAIDI of 75 min will be used in calculations. Thus, it follows that the cost-based benefit of the field crew management application is the difference between the outage cost on the feeder in the case of remote-controlled disconnectors and that of field crew management. By equation (1)-(3), the initial data in Tables III and IV and the new SAIDI assumptions of 75 min (earth faults) and 50 min (short-circuit faults), respectively, the difference between the outage costs equals approximately 1.5 k€/ feeder,a.

Consequently, the cost benefit per feeder is higher for the use of fault location application than for the field crew management application. However, in cases of earth faults, where the use of fault location application in the DMS is not possible, field crew management can play an important role especially, if there are no remote-controlled disconnectors on the network. If there are remote-controlled disconnectors, then the control room can perform fault location actions, compensating the work of technicians.

4.3 Fault reporting

The importance of fault reporting becomes vital in particular during extreme conditions (e.g. storms), with simultaneous faults in the network. The target is to know the number and details of the faults so that redevelopment actions can be planned and customers and market authorities kept up-to-date. Fault reporting is a DMS application by which it is possible to achieve benefits in the cost of labour and outage costs.

In the benefit calculation of the DMS fault reporting application, two long-term scenarios are analyzed. Scenario 1 represents the realization of outage costs of one feeder during 40 years before and after renovation when fault reporting is used. Scenario 2 represents the same case with the exception that fault reporting application is not used, and thus, the renovation of feeder sections is carried out in random order. In both scenarios, two cases of long-term feeder outage costs will be calculated:

(1) the total outage cost for one 40 km feeder for a period of 40 years; and

(2) the total outage cost for one 40 km feeder for a period of 40 years after renovation.

As a result of renovation in both scenarios, it is assumed that the failure rate of each feeder section will be half of its previous value. Finally, the present values of the average discounted outage cost benefits for a period of 40 years for both scenarios are compared.

First, it is assumed that the feeder (40 km) is divided into 40 sections of equal length, and one section of the feeder is reconstructed per year, which means that the feeder section is transferred to the roadside. Second, each of these sections has an individual fault rate based on an assumption that the average fault rate is 7 psc/100 km, a. Again, by applying equations (1)-(3), the initial data in Tables III and IV and the SAIDI assumption of 1 h, we calculate the outage costs for each feeder section. The outage costs are calculated for each feeder section for 40 years with the respective discounted value. Table V summarizes the outage costs of each feeder section for 40 years prior to and after renovation. Thus, the total outage cost for one feeder for 40 years sums up to approximately 0.9 M€ prior to renovation.

After renovation, it is assumed that the number of high-speed automatic reclosings decreases from 50 to 40 pcs/100 km, a, and the number of delayed automatic reclosings decreases from 20 to 15 pcs/100 km, a. As a result of renovation, it is further assumed that the failure rate of each feeder section will be half of its previous value.

Feeder section	Fault rate (pcs/km, a)	Outage cost (k€, 40a/feeder section)	Benefit (k€, 40a/feeder section)
Prior to renovation			
1	0.2	47.8	
2	0.1	28.3	
3	0.1	28.3	
...			
40	0.05	18.5	
		897,4	
After renovation			
1	0.1	27.5	20.2
2	0.05	17.9	10.4
3	0.05	18.5	0.98
...			
40	0.025	18.5	0
		757.9	139.5

Table V. Scenario 1, outage costs prior to and after renovation

Consequently, the feeder section that has the highest fault rate is renovated in the first year and the feeder section that has the lowest fault rate is renovated last. Further, the assumed interruption time per feeder is still 1 h. Hence, outage costs for the feeder after renovation are calculated so that the first feeder section is in the network one year before it is restored causing outage costs with a fault rate of 0.2 pcs/km, a, and 39 years after restoring causing outage costs with fault rate 0.1 pcs/km, a.

Table V summarizes the annual outage costs of each feeder section after the renovation with discounted values. Finally, the total outage cost for one feeder for 40 years equals approximately 0.76 M€ after renovation. Thus, when performed in the optimal way, the benefit from fault reporting in the case of renovation during a period of 40 years the total benefit is approximately 140 k€ (Table V).

Consequently, we shall examine the scenario where fault reporting is not used, and feeder sections are restored in random order. Discounted outage costs for feeder sections prior to and after renovation are presented in Table VI.

Thus, the benefit from the use of fault reporting when comparing Scenarios 1 and 2 equals roughly 140-123 k€ = 17 k€ in present value during 40 years and 0.5 k€,a per feeder, respectively.

As a conclusion, we have to consider that this cost benefit of approximately 0.5 k€/feeder represents a theoretical maximum, whereas in real conditions the actual age of the feeder should be taken into account. In this study, the target is to calculate and show the approximate cost values of benefits achievable from the use of DMS applications both as such and compared with each other. Further, benefits of fault reporting not considered in the above calculations also include savings in man-years, as the fault reports are gained automatically from the DMS without manual analysis.

4.4 Reconfiguration

Network reconfiguration allows optimization of the network topology and functionalities in various unplanned and planned network states. Successful network reconfiguration (preferably on a yearly basis) can facilitate in reducing both loss and outage costs.

Feeder section	Fault rate (pcs/km, a)	Outage cost (k€, 40a/feeder section)	Benefit (k€, 40a/feeder section)
Prior to renovation			
1	0.08	24.4	
2	0.06	20.5	
3	0.05	18.5	
. . .			
40	0.05	18.5	
		897,4	
After renovation			
1	0.04	15.2	9.2
2	0.03	13.5	6.9
3	0.025	12.8	5.7
. . .			
40	0.025	18.5	0
		774.6	122.8

Table VI.
Scenario 2, outage costs prior to and after the renovation

The cost-based benefits of network losses obtained by the use of the DMS reconfiguration application are calculated based on the assumption provided by the expert interviews, according to which it is possible to decrease the losses of the annual energy consumption by 10 percent when the network is reconfigured for the first time. Benefits achievable from reconfiguration are calculated by equation (6). When losses are 3 percent of the annual energy consumption, the price of loss energy is 45€/MWh, the peak load of the feeder is 2 MW, the peak operating time of the load is 3,000 h, and the cost of losses is approximately 8 k€. The cost of losses in the case of the annual energy consumption 2.7 percent equals approximately 7 k€. Thus, the achievable cost benefit equals roughly 1 k€/feeder,a. Hence, it should be highlighted that these cost benefits are realized at once. As a comparison, the realization of total benefits in the use of fault location application requires multiple operations.

4.5 Summary of the calculated DMS application benefits

The benefits calculated above for each DMS application are summarized in Table VII.

The assumptions used in the calculations are based on in-depth network expert interviews, by which also the calculated results have been validated.

Initial data used in the calculations consisted of actual network data from the case utility Suur-Savon Sähkö (SSS). SSS represents a typical North-European rural distribution company containing 39 primary substations and 235 20 kV feeders that operate under the same conditions as presented in this study. SSS has an electricity distribution network of 25,400 km with 97,000 electricity end-users and a total 1,200 GWh consumption. The authors believe that both the presented outage-cost-based analysis method and the results obtained can be utilized to support evaluation and decision making of DMS investments in similar distribution utilities.

Achievable cost-benefits of the use of the DMS applications compared with the required DMS and relay investment costs are further presented in the light of the actual number of feeders in the case electric utility, and hence shown in Figure 2. The annuity calculations feature a network section belonging to the case electric utility (SSS) that contains three substations and five feeders per each substation. It follows that each benefit presented in Table VII is multiplied by a factor of 15 (3×5). Hence, the modeled network section is very small compared with the total network of the case company consisting of over 200 feeders. Any realizable maximum cost benefits in this modeled network section are far greater in the actual overall network. Thus, also if the realized actual benefits were smaller than those of the theoretical maximum, the benefits would be considerable in total.

The annual investment cost (annuity) of the DMS including the annual cost of maintenance is calculated by equation (7) assuming that the lifetime of the DMS is five years, the interest rate is 5 percent, and the investment cost of the system

Application	Benefit (k€/feeder, a)
Fault location and restoration	2.5
Fault reporting	0.5
Reconfiguration	1
Field crew management	1.5
Total benefit, all applications	5.5

Table VII. DMS application benefits per feeder

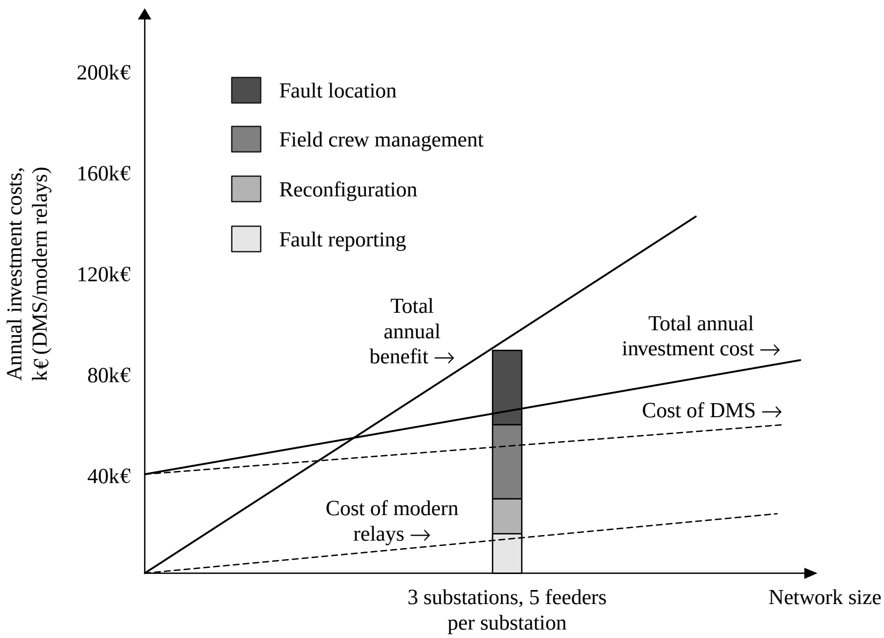

Figure 2.
Annual investment costs of the DMS and relays in the chosen network section (15 feeders) of the case electric utility compared with the benefits achievable from the DMS applications

is approximately 160 k€. In order for the DMS to function in the optimal way in all the applications, modern relays are required in the network to enable an analysis based on fault current data. The annuity of the modern relays is calculated by equation (7), and the initial data consist of an investment cost 150 k€ (15 relays), a 20 years' lifetime of relays and an interest rate of 5 percent. Figure 2 shows the maximum cost benefits achievable by the use of the DMS applications calculated above. In practice, the cost benefits are not purely linear, as shown in this simplified model. As the number of feeders in this example case is 15, also the calculated cost savings per application are multiplied by a factor of 15.

Further, the amount of automation in the network enables more advanced use of the DMS. The line representing the annuity of the DMS is not steep, as the investment costs can be seen as a function of network size. In situations, where there are no modern relays in the network that would be able to transmit the fault current information, the overall cost of the DMS is considerable.

Some considerations should be highlighted with respect to the sensitivity analysis of the case study. First, the network parameters (Table III) are sensitive to calculation results. A theoretical feeder normally differs from an actual feeder in the network with respect to the actual structure and power. However, numerically this is challenging to take into account in theoretical calculations. A practical example could the fact that on short feeders with high powers, the outage costs remain small.

A second viewpoint to the evaluation of sensitivity includes the issue of fault frequency. The higher the frequency of faults in the network is, the higher the possibility of cost savings in the form of DMS benefits. Finally, also the parameters used for calculation are sensitive with respect to t_i. In cases, where t_i for interruption duration is considerable, such as in major storms or blackouts, there are also considerable benefits to be achieved and the calculation is thus quite sensitive. In order for DMS benefits to be actually capitalized in these extreme conditions, proper utilization of the application should be ensured. On the other hand, t_i is linear by nature, whereas in cases with short interruption times, both the benefits and the level of sensitivity are limited.

Outage cost parameters utilized in the study, as such, are defined by national energy authorities, and can thus vary from country to country. However, the methodology presented in this study for outage-cost-based evaluation is generic. Further practical experiences imply that the size of a DMS investment is often proportional to the actual network size (number of feeders) and the required amount of DA. Thus, also the amount of capitalizable cost benefits of DMS is proportional to these variables.

The best results can be obtained when fault location is used in the DMS and there is appropriate competence to use the applications. However, based on the expert interviews, in which the calculated results were evaluated, it seems that the benefits are not realized in full in the utilities. The factors behind the gap are identified to include deficiencies in the DMS system and competence issues.

5. Discussion and evaluation

By capitalizing the applications of the DMS, it is possible to acquire considerable benefits in outage costs (Table VII). The most beneficial DMS applications based on the calculated results are fault location and field crew management. One considerable limitation in realization of the calculated benefits in fault location application is the fact that currently in a typical medium-voltage neutral-isolated system, where fault location is based on measuring the fault current, earth faults cannot be located by the application. However, by configuring settings in modern earth fault relays, it is possible to treat the earth faults as short-circuit faults. Thus, also the earth faults can be located by the DMS application and the cost benefit becomes even greater.

Figure 2 shows a theoretical distribution of DMS-related annual investment costs and their breaking point with the expected maximum-level of benefits. The theoretical maximum level of benefits can be modeled to represent different utility cases for example by modifying the amount of automation in the network, which in turn affects SAIDI in each DA and DMS function. Hence, purchase of a DMS does not automatically trigger an access to the DMS benefits.

The interviews with the case utility SSS imply that DMS is suitable for normal conditions, and the availability of benefits is emphasized in normal situations such as single fault location and reporting. By contrast, the benefits are currently far more marginal under extreme conditions, such as in the case of major disturbances, as significant problems were experienced with fault reporting and fault location applications. According to the case utility SSS, the theoretical cost benefits at the feeder level shown in Figure 2 are realistic, however, not yet reached. The reasons behind the gap to maximum benefits largely depend on the problems with fault reporting and malfunctioning of fault location in major disturbances. Thus, in a utility where half of the faults are assumed to be caused by major storms, the benefits acquired from the DMS are evidently smaller than the theoretical situation in Figure 2.

In the case of SSS, the actual cost benefits achievable of the DMS were calculated according to the methodology presented. The benefits of each DMS application presented in Table VII were multiplied by the actual number of feeders in the network (235) and the maximum amount of cost benefits from the DMS equaled roughly 1.4 M€

as shown in Figure 3. The interviews with SSS confirmed that the actual value of benefits is currently less than 1.4 M€,a mainly owing to the malfunctioning of the applications in major disturbances. Continuing, it is interesting to compare the calculated DMS cost benefits with other running annual costs in the utility. As seen in Figure 3, benefits achievable from DMS applications can be substantial compared with the present outage costs and operational expenses. Figure 3 presents the average value of outage costs (M€,a) during years 2005-2006 and the average value of operational expenses (M€,a) during 2003-2006.

Finally, in the case of SSS, the cost-based benefits achievable from the addressed DMS applications equals roughly 25 percent of the annual outage costs and 10 percent of the respective operative costs. As such, the annual measurable benefits from the use of DMS applications are considerable. Distribution utilities that are considering purchase of DMS are encouraged to estimate the achievable DMS benefits according to the presented methodology. On the other hand, distribution utilities with a DMS already in service are encouraged to evaluate the actual benefits especially in field crew management and fault location applications in the hope of possible quick wins.

6. Conclusion

The study examines the key outage-cost-influencing applications of the DMS and analyzes the benefits provided by them. Applications discussed include fault location and network restoration, fault reporting, field crew management, and reconfiguration. It was shown that the greatest cost-based benefits were obtained from the fault location and field crew management applications.

The interviews of network experts support the obtained theoretical calculated results; however, these maximum levels of cost benefits have not yet been reached in the case utility SSS. Empirical findings from the case utility show further that the

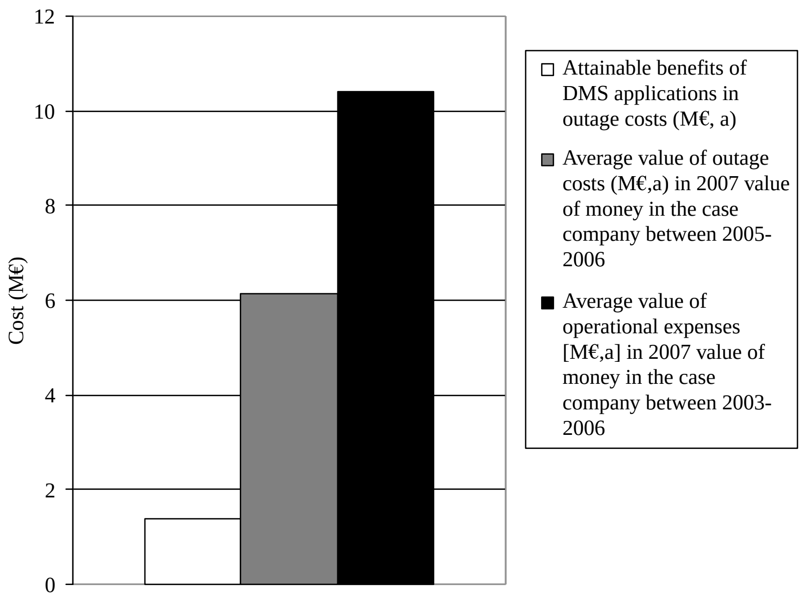

Figure 3.
Outage costs and operational expenses of SSS compared with the benefits achievable from DMS applications

DMS is best applicable to normal conditions such as single fault location, whereas in emergency situations, the benefits are only marginal.

The study suggests the use of outage-cost-based calculations supported by a SAIDI analysis for evaluation of DMS application benefits. The benefit evaluation method is supported by the current economic regulation and overall cost management in utilities and can widely be utilized to support evaluation and decision making of DMS investments in distribution utilities.

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