FUNCTION ANALYSIS - A COST EFFECTIVE MAINTENANCE METHODOLOGY IN MEDIUM VOLTAGE INSTALLATIONS

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ABSTRACT

After a long period of Rate of Return (ROR) regulation in Norway, a revenue cap regulation was introduced in 1997. The revenue cap, as well as the owner's increased focus on profit imposes many Norwegian network companies to considerable cost reductions. Function Analysis is a methodology that may reduce operational and maintenance costs in MV substations. The methodology derives information about the condition of a given component by using the component's status information, with the purpose to find the probability of a function failure. Combined with a risk analysis, the methodology will give a more reliable decision tool for operation and maintenance.

1. INTRODUCTION

The Norwegian network companies have from 1997 been regulated according to a revenue cap model [1]. The revenue caps take into consideration the historical level of costs of operations, maintenance and investments for each company individually, determined by the Norwegian Water Resources and Energy Directorate. From 2001 the revenue caps are quality dependent through the Cost of Energy Not Supplied (CENS) arrangement [2]. The revenue caps are adjusted in accordance with the customers' interruption costs (in principle). This regulation model is incentive based, meaning that the companies will be better off by balancing their internal costs and quality of supply towards a socio-economic optimum.

Since the regulator decides the maximum revenues, the companies can only increase their profits by reducing their costs. As a result of this regulation there is a strong focus on reducing the costs. This paper proposes a new method for cost-effective maintenance in MV installations:

Function Analysis is a methodology, which derives information about the condition of the primary and secondary equipment by the use of status information. The information is available via the Substation Automation System, the feeder automation and control units and it is used for the Function Analysis together with statistical and probabilistic analyses. The Function Analysis, combined with a risk analysis gives the network companies a better decision basis for the operation and maintenance of the primary equipment and the protection system. A decisive factor in the Function Analysis is the use of probabilistic methods. By combining the information about the equipment's condition, together with statistical analysis, it is then possible to predict the equipment's probability for a correct function when required.

The proposed methodology of Function Analysis is outlined in Ch. 4 and the technical solutions are described in Ch. 5. As a motivation for development of the Function Analysis the Norwegian regulation regime is described in Ch. 2, while Ch. 3 gives some highlights from the fault statistics considering the protection system.

2. A NEW DRIVE TOWARDS COST EFFECTIVE SOLUTIONS

The network is defined as a natural monopoly and is regulated in most countries. Like many other countries, the Norwegian distribution companies are regulated through a Rate of Return regime (ROR). Experience shows that this regime provides very little risk related to investments, operations and maintenance. The ROR is fixed, meaning that the customers therefore have to cover for excessive investments and high operational costs. As the rate of return is determined from the book value, it gives the grid companies incentives for investing in excess capacity.

After a long period of ROR regulation in Norway, a combination of incentive-based regulation and performance-based ratemaking (PBR) was introduced in 1997. This model combines revenue cap regulation with benchmarking and earnings sharing mechanisms. The ROR is no longer fixed, but limited to minimum 2 % and maximum 15 %. In the future, profit will to a larger extent depend on the companies' ability to reduce costs.

To give financial incentives to maintain acceptable quality of supply, the Norwegian Water Resources and Energy Directorate (NVE) has introduced a revenue cap adjustment, based on estimated energy not supplied (ENS) and average interruption cost data (the CENS arrangement). The adjustment is done due to the following formula [2]:

$$CENS = ENS \cdot k_w$$

where

CENS	the reduced revenue because of an interruption [NOK]
ENS	estimated energy not supplied [kWh]
k_w	specific cost per unit rate [NOK/kWh]

The CENS is based on interruptions of duration > 3 minutes for medium/high voltage end-users and at the distribution transformer level. The arrangement has so far separated only between residential/agriculture and commercial customers. Interruptions due to both disturbances and planned disconnections are included, differing between not notified and notified interruptions as illustrated in Table 1.

TABLE 1: CENS cost rates per 2002, NOK[1]/kWh

	Not notified interruptions	Notified interruptions
Agricultural/ Residential	4,00	3,00
Industry/ Commercial	50,00	35,00

One of the main challenges is how to make the best use of the existing network. For a long time maintenance and replacement was a question of technical matters, but have now turned towards corporate finance and profitability. The revenue cap, as well as the owners' increased focus on profit imposes many Norwegian network companies to considerable cost reductions. Pressure is put on maintenance and replacement costs since these cost elements are, at least in the short run, the easiest to reduce. A reinvestment postponed for five years will give a financial profit of approximately 35 %. However, the uncertainties related to how the technical conditions develop are large. Combining these with the considerable financial consequences of failures, the network companies face large financial risk under the revenue cap regulations.

3. PROTECTION FAULT STATISTICS AND THE ECONOMICAL CONSEQUENCES

Some highlights from the Norwegian fault statistics for the period 1990 – 1999 were presented at CIRED 2001 [3], considering incorrect operation of the protection system. The results presented covered mainly the transmission levels 33 – 420 kV. Recently a new study is performed of the protection faults registered in the period 1997 - 2001 in the FASIT reporting system [4]. The study covers the MV levels 1 – 22 kV and the sub-transmission levels 33 - 110 kV. The results supplement the previous study.

The statistics show that most of the protection faults can be classified as unwanted operations. These incorrect operations amount to 50 % of the protection system faults at 33 – 110 kV levels and 46 % at 1 – 22 kV. There is also a minor portion of missing operations: 6 – 9 %, while more than 40 % of the protection faults are not specified in the statistics. The number of incorrect tripping from the protection system is about 10 % for both conventional and numerical equipment [5]. So far the new technology has not led to less faults, but the types of faults have changed. Incorrect operations of the conventional protection are mainly caused by technical faults (ageing). The numerical protection system faults are however almost exclusively human related. The major failure causes are incorrect setting while putting the equipment into operation and faults introduced during work in the substations. There is still a large portion (30 – 40 %) of the faults where the cause is not specified at the voltage levels 1 – 110 kV.

If we look at the consequences of protection system faults in terms of energy not supplied (ENS) to end-users, we find that incorrect operation of the protection system contribute to as much as 18 % of the ENS at the transmission levels 33 – 420 kV as a whole [5]. The relative amount of ENS caused by protection system faults decrease by decreasing voltage levels. The statistical material for the levels 1 – 22 kV is unfortunately incomplete, especially for ENS. It is previously estimated that incorrect operations amount to 10 % of ENS caused by 1 – 22 kV [3]. However, the distribution system as a total contributes to about 75 % of the total ENS. Related to the Cost of Energy Not Supplied (CENS) arrangement in Norway, protection system faults count for about 8 % of the total CENS cost of approximately 90 million Euro per year, including all voltage levels [6].

The fault statistics show that incorrect operation of the protection system is quite important for the quality of supply. The network companies have so far not been able to achieve the potentials for reduced maintenance, provision of information etc related to using numerical protection. The fault statistics indicate that the new technology is used and maintained as the conventional. However, the human related incorrect operations of the protection system can be avoided by taking certain measures. Some of these are:

- *Evaluation of the equipment's condition*
- *Plans for protection system performance*
- *Improving working procedures*
- *More reconnection possibilities in the network*
- ***Fault analysis as basis for maintenance***
- *Numerical equipment gives new possibilities*
- *Increased automation*

In this paper we will focus on fault analysis as a basis for maintenance (function analysis) and increased automation.

4. FUNCTION ANALYSIS MAINTENANCE METHODOLOGIES

The maintenance in a substation has traditionally been done as a time-based and not as a condition-based maintenance. Many network companies have now started using condition-based maintenance.

Function Analysis [7] is a condition-based methodology with the purpose to find the probability of a function failure and to use this knowledge in the maintenance considerations. The new MV substations automation system gives a lot of information both from primary and secondary equipment as shown in the table below. By combining the use of information from the substations and the feeder automation units together with the probability and risk considerations, it is possible to create a maintenance system for most of the primary and secondary equipment.

1 1 Euro ~ 7,5 NOK

TABLE 2: Protection, control and monitoring functions

Protection functions	Control functions	Monitoring functions
Over current	Sectionalising Switching	Breaker information
Ground over current	Automatic Sectionalising Switching	Power quality
Negative sequence	Loss of voltage	Fault curves and fault information
Directional over current	Load shedding Load restoration Frequency switching	
Frequency		
Other protection functions…		

How is it possible to use this information in a maintenance system for both primary and secondary equipment? Or is it at all possible? The principles of the Function Analysis methodology are described in the following paragraphs.

Function Analysis

Function analysis is a methodology that can tell us something about the behaviour of the primary and secondary equipment based on gathered information.

Central tasks or elements in the function analysis methodology are:

- Fault analysis
- Function control
- Function supervision
- The consequences of function failure

Fault analysis is an investigation of the power system performance under normal or faulty conditions. Numerical technology gives increased possibilities with reference to fault analysis, especially in comparison with electromechanical and static techniques. This is due to the large possibilities for information as illustrated in Table 2. A primary fault is the best way for the utility to test the fault clearing system including the protection settings. Using the comprehensive information in the bay units, it is possible to analyse the different faults more accurately than before.

Function control is a planned active action from the dispatch center. By activating for example a breaker and combining this information with statistical material it is possible to say something about the breakers condition.

Function supervision includes the normal signals during normal and faulty situations.

Figure 1 shows the main elements in function analysis.

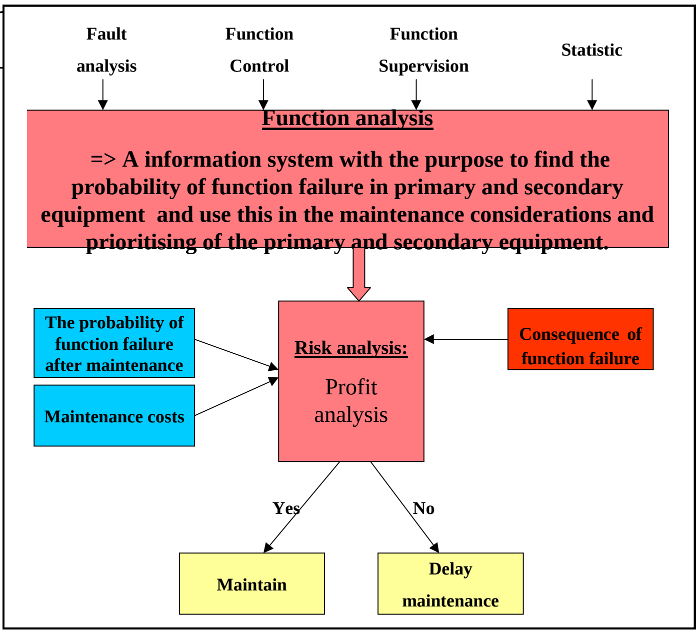


Figure 1 Function Analysis methodology, the main principles

Function analysis makes use of the available information to make an evaluation of the performance of the different components in a substation. The purpose is to control the equipment's behavior. This is carried out during faulty and normal situations. It is possible to do this automatically or manually. One manufacturer is now already developing automatic function and risk analysis connected to their SCADA system.

Risk and profit analysis

Risk and profit analysis in Figure 1 will be a combination of the results from the function analysis, economic demands, operational consequences in the power system etc. The result of the risk and profit analysis is a probability evaluation of the consequences of delaying or not the maintenance of different components such as breakers, protection and control equipment. Central elements in the risk and profit analysis are:

- The probability of function failure after maintenance
- Maintenance costs
- Consequences of function failure
- Statistical material of different components

A probability model should fulfil the following requirements:

- The model must govern the wanted details in a simple and clear way.
- The model must govern large and complex system without the user loosing the overview.
- The model must be flexible.
- Economy must be a part of the analysis.

The choice of a probability model will be investigated in the further work.

Maintenance optimisation

The results from function analysis and risk/profit analysis can be used as an input in the condition based maintenance and can help the network companies with the evaluation of the economical consequences by changing the maintenance as a basis for finding the optimal level of maintenance.

The combination of function analysis with risk analysis as proposed in this paper is a methodology under development. A recently started research project will be working with the elements concerning information handling, probability models and risk analysis. The project is carried out by SINTEF Energy Research, in cooperation with the Norwegian Transmission System Operator and network companies. The following chapter describes the technical solutions necessary for the Function Analysis methodology.

5. TECHNICAL SOLUTIONS

The traditional communication system is more an operating system than a system for other purposes. We believe that a command communication system will be the future system for all tasks. However the system will be divided into different areas. In this paper we are focusing on the central platform for function analysis and automatic solutions.

The central platform
From our point of view, the requirement is a combination of an on and off-line system. It is also an advantage to make a separation between the system for transmission substations and the MV substations. In the future we will focus on the on and off-line communication for MV substations and the possibilities for information handling and automatic solutions. Figure 2 shows some principles for common communication infrastructures.

Substations with RTU solutions and substations with serial communication must in this approach be treated differently to get a common platform for probability considerations.

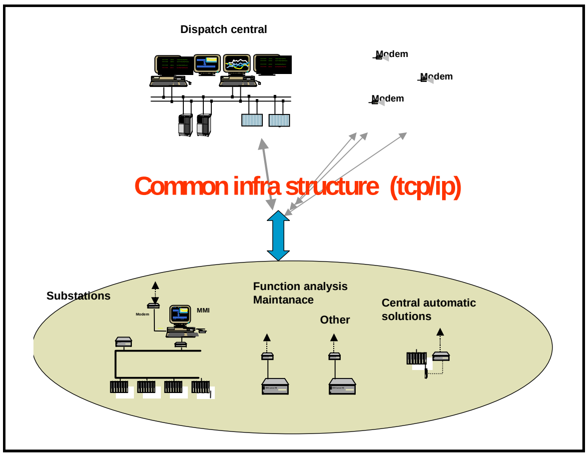


Figure 2 Communication principles

On-line serial communication with MV substations. The MV substations will in the future locally have all necessary evaluation software implemented, for example for fault analysis and automatic solutions. The central server gathers all information from the terminals, stores it in a database and provides the adequate formats to the information. On-line communication gives possibilities for automatic solutions and function analysis.

Automatic solutions. By using on-line communication the network company gathers a lot of information in real time. It is possible to use this information in the central platform to create an automatic area restoration system. Today the local information is being used in local reclosing systems. The central platform solutions give the companies possibilities to change the operation automatically. This could reduce the CENS cost and increase the reliability of supply to the customer. The information gives further increased possibility to operate the distribution system as a meshed system. Online communication supervises adequate parameters and acts automatically if something abnormal happens.

Function analysis. Function analysis and probabilistic considerations should be handled locally. The central platform object can connect the result from the local function and risk analysis and store it in the maintenance database. The information is also available for the dispatch centre and gives possibilities regarding strategic maintenance and operation of the different components in the network. The online communication system gives the company possibilities to implement an expert system in the central platform to handle function analysis information and automatic (rebuilding) area systems.

Figure 3 illustrates a solution of the information flow.

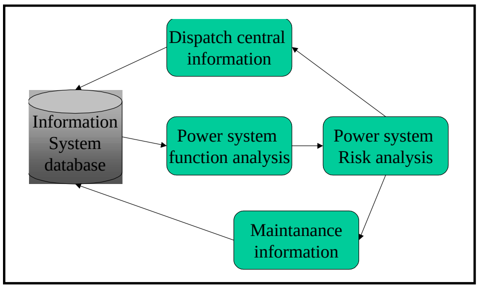


Figure 3 Information flow for function analysis

On-line communication with RTU in MV substations. An RTU solution does not give possibilities for automatically function analysis and automatically handling of information in the central platform. The necessary information for function control and function supervision can be used, but we do not recommend this solution. In MV stations with RTU solutions the function analysis should be a manual process together with the risk- analysis. The results are implemented in the maintenance database. For this purpose an off-line communication system is necessary.

Off-line communication with MV substations. The offline system has to be used for function analysis in MV substations with RTU solutions. An information system provides a fully independent local server. It is possible to access the local units from remote. The units have all necessary evaluation software implemented already, for example for function analysis and automatic rebuilding area solutions. The server gathers all information from the terminals and stores it in a database and provides the adequate formats to the information. The system stores:

Real-time Data
- Signals
- Events
- Dynamic values

Monitoring information
- Diagnostics
- Trends
- Documents
- Information from the primary components
- Fault current and voltage values.
- Capability to compare values from different stations
- Disturbance information
- Automatic fault analysis / expert systems

Off-line communication with the substation does not give possibilities for automatic function analysis and a central automatic solution. A manual function analysis and a local reclosing system is of course possible

The local platform

It is necessary to get a common platform for substations with serial communication and RTU solutions. In the first case an automatic solution handled by a sort of tool described previously is possible. In the case of an RTU station a manual solution is necessary.

By the use of offline communication it is possible to collect all information to use in the function analysis process. A manual analysis of the information is necessary. To get a command platform, this information has to be put into a function analysis and risk analysis tool in order to get the information on the same platform as for automatically solutions.

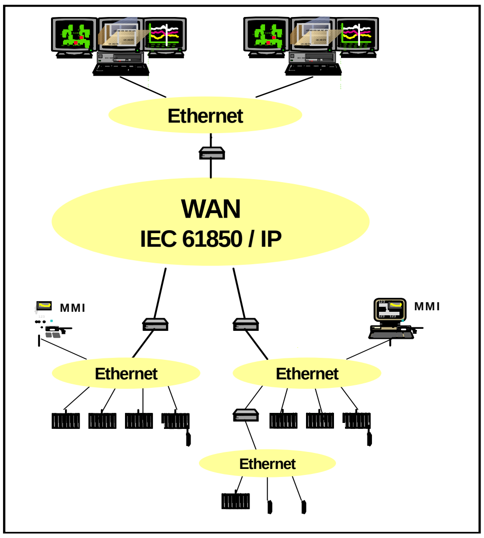
Combining the result from function analysis locally with probability considerations is it possible to say something about the technical and economical risk operating the different components without doing any changing in the technical solutions and without maintain the different components.

Communication system

The communication to the MV installations is an important part of implementing the suggested solutions described in this paper. Function analysis and automation solutions depend on the on- an off-line communication. The IEC 61850/IP protocol gives us the needed possibilities.

Figure 4 shows a solution in principle. A solution could be a total communication system that includes different areas such as the dispatch centre, transmission substations, MV substations, expert system, function analysis etc. All these elements may be separate areas in this mentioned total communication system.

Figure 4 Possible solution of the communication system



6. CONCLUSIONS AND FURTHER WORK

In the future, profit will to a lager extent depend in the companies' ability to reduce costs. One of the main challenges is how to make the best use of the existing network and how to do the right investments to reduce the lifetime costs of the different components in the network. The protection fault statistics from Norway shows us that unwanted functions give quite large contributions to CENS.

In this paper we have presented a methodology to reduce maintenance and operational costs. Function Analysis can be used to find the probability of a function failure in MV substation equipment. By combining the use of information from the substations together with risk considerations, it is possible to create a maintenance system for MV substations. From our point of view automatic solutions could reduce the CENS costs today and in the future.

It remains some work to establish the presented method, especially concerning information handling, probability models, cost benefit and risk analysis.

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