FAULT STATISTICS AS A BASIS FOR DESIGNING COST-EFFECTIVE PROTECTION AND CONTROL SOLUTIONS

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ABSTRACT
This paper gives some results from ten years of statistics of protection system failures at the levels 33 – 420 kV. The majority of failures are unwanted operations. About half of these are caused by human failures. Incorrect operation is also a large contributor to energy not supplied to end-users. Examples of performance indicators are given showing that the security of transformer protection is low. The paper also discusses measures to improve the protection system performance and the quality of supply.

KEYWORDS: Protection system failure, unwanted operation, energy not supplied, performance indicators

1. INTRODUCTION

Protection and control (P&C) are important components in the operation of the power system regarding how the system acts upon faults and disturbances, and as such for the quality of supply. The increased focus on the quality of supply has therefore brought new attention to protection and control solutions as well as on automation. On the other hand there is a strong pressure to reduce the costs and there is a need for finding cost-effective solutions. In Norway socio-economic optimization is a fundamental basis for network development and operation. The economic loss of energy not supplied (ENS) is an important factor in this optimization. This is handled through the CENS arrangement [1], where the network companies' revenue caps are adjusted in accordance with the customers' interruption costs (in principle). CENS is calculated as the product of average interruption cost rates and ENS caused by long interruptions (> 3 minutes).

The Norwegian fault statistics show that P&C equipment in the 33 – 420 kV transmission system has a large number of incorrect operations and is a significant contributor to energy not supplied (ENS) and thereby the end-users' costs of interruptions. The majority of the incorrect operations are unwanted operations, and there are a considerable number of missing operations.

As a result of the focus on P&C solutions it is becoming important to make trade-offs between investment and maintenance costs and costs associated with incorrect operation of the protection. The fundamental basis for such judgments is the fault and interruption statistics. A lot of attention has been paid to the monitoring of the quality of supply and the reliability of the network components since the deregulation and unbundling of the electricity sector was put into force in Norway in 1991.

This paper gives some aggregated results (section 2) from the statistics of incorrect operations of protection and control. The results cover the levels 33 – 420 kV for the period 1990 – 2000. From 1999 all protection responses 132 – 420 kV (correct and incorrect) have been monitored. This allows for the calculation of the dependability and security indices defined by CIGRE [2]. Examples of indices for the two years 1999 – 2000 are given in section 3. The protection failure statistics will be an important basis for defining measures to improve the performance of P&C solutions as well as ways to achieve cost-effective solutions. This is discussed in section 4.

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2. FAULT STATISTICS 33 – 420 kV

Since 1995 the network companies have been reporting key figures to the regulator regarding quality of supply for the end-users. The key figures are number and duration of interruptions > 3 minutes and energy not supplied (ENS), according to the FASIT specification [3].

Reporting of faults and outages of components in the power system is mandatory at the transmission levels 33 – 420 kV, also incorrect operation of P&C equipment. The registrations are made by the Norwegian transmission system operator (Statnett). Statnett's fault and disturbance information system is coordinated with FASIT, the standard used by all network companies at the lower transmission levels 33 – 110 kV and the distribution levels 1 – 22 kV. Reporting of faults and outages of components is voluntarily at the distribution level, and today incorrect operation of the protection at this level is seldom registered in the fault statistics. Even if the registration at the 33 - 110 kV levels is mandatory the data basis is not complete in the sense that not all incidents are registered.

Protection system failures are part of the total fault statistics in Norway. The information recorded on each incorrect operation (or malfunction) of P&C comprises the following:

- Date and time
- Failure number during the outage
- Related high voltage component
- Type of protection or control equipment
- Voltage level
- Failure causes
- Failure type (type of incorrect operation)
- Outage/Repair time
- Energy not supplied

A study of incorrect operation of P&C in the period 1990 – 1999 was carried out in 2000. The results are reported in [4]. In this period it was a total of 4900 incorrect operations on protection and control equipment at the 33 – 420 kV levels. This number also includes P&C for generating units. About 60 % of the malfunctions are related to the protection while 40 % is related to the surrounding control equipment. The results show that the number of protection system failures is higher than the number of faults on any of the high voltage components, even overhead lines.

In this period most of the incorrect operation of P&C were unwanted operations. Figure 1 shows the types of failures for the different types of protection. The figure shows that the major failure type is unwanted operation, particularly for differential protection. About 70 % of all the unwanted operations in the statistics are primary faults. This means that they have directly led to outages in the power system. The same figure for missing operations is 45 %. The rest of the incorrect operations are secondary or higher order faults, meaning that they are discovered during outages.

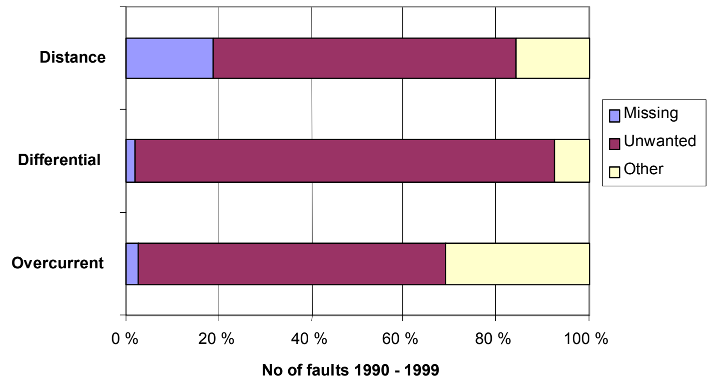

Figure 1 Incorrect operation of different protection

Figure 2 shows the failure causes for unwanted operations of P&C. About half the unwanted operations are caused by human activities during operation of the power system, or related to testing and setting of the P&C. Human causes count for about 20 % of the missing operations too. These are mostly incorrect settings when the equipment is put into operation. Technical equipment counts for about 40 % of the unwanted operations and more than 60 % of the missing operations (cause mostly unspecified). 11 % is in the category "other/unknown", where 8 % is not identified or reported.

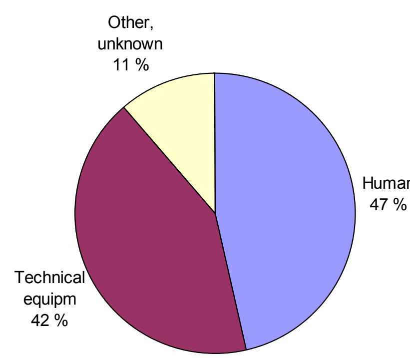

Figure 2 Main causes for unwanted operation

The statistics give information about consequences of incorrect operation of P&C in terms of energy not supplied (ENS) to end-consumers. The interruption statistics [5] show that ENS per year for Norway as a whole has been 33,4 GWh on average in the period 1995 – 1999. 60 % is due to fault outages and 40 % due to planned disconnections. Figure 3 shows the distribution of the total annual ENS due to **fault outages** in Norway. 27 % of this ENS is caused by the transmission system 33 –

420 kV. P&C is the second largest contributor to ENS, after overhead lines, at these voltage levels, and the P&C malfunctions amounts to 17 % of the ENS caused by the transmission system 33 – 420 kV. This corresponds to about 5 % of total ENS caused by fault outages. Unwanted operations count for more than half of this ENS while missing operation makes nearly 15 %. The rest is mostly unknown or not explained. Protection for 132 kV components is the largest contributor to ENS due to P&C.

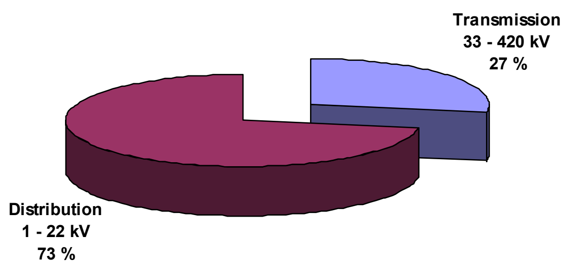

Figure 3 Energy not supplied due to fault outages

Related to the CENS arrangement, ENS caused by incorrect operation of P&C counts for about € 2,8 million per year at the levels 33 – 420 kV. It is assumed that P&C for 1 – 22 kV contributes to 10 % of ENS at the distribution level, making about € 4,4 million per year [4]. Thus, the total contribution to customers' interruption costs from protection system failures is 8 % of the total CENS cost of approximately € 90 million per year.

The types of protection in the Norwegian power system today are mostly electromechanical and electronic devices. These are gradually changed to modern numerical units. Lately the Norwegian Transmission System Operator (Statnett) has been able to attach the protection failures to the faulty equipment itself. Combined with information on type of protection technology it is possible to provide statistics for different types of technologies. So far this is possible only for distance protection 132 – 420 kV.

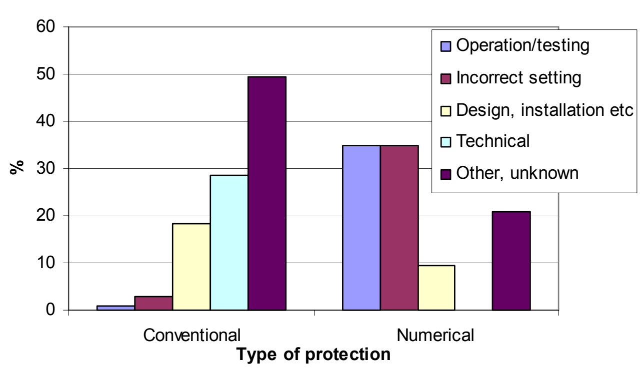

Figure 4 Distance protection failure causes 132 – 420 kV

Figure 4 shows the failure causes for conventional (electronic and electromechanical) and numerical protection for the period 1999 – 2000. The figure shows that incorrect operations of the conventional equipment are dominated by ageing or other technical causes and by failures during the design and installation phase (human causes). About 50 % of the incorrect operations of conventional protection are however unknown. This means that the failure cause is not identified/reported. The numerical units are dominated by failures during operation/testing (35 %) and incorrect setting (35 %) while putting into operation. So far there are not registered any technical failures. This figure covers only two years of statistics, but the limited experiences show that the largest groups of failure causes for numerical devices are human. This is probably due to limited competence on the implementation and use of the modern numerical protection in the power system. In a recent CIGRE publication [6] Statnett has reported experiences with modern protection schemes at 300 – 420 kV.

3. RELIABILITY OF PROTECTION SYSTEM

The reliability of P&C is of high importance for the quality of supply and for the amount of ENS. CIGRE WG 34.01 has defined performance indices making it possible to quantify the reliability of the protection [2]. The performance indices measure the probability of not having a failure to operate (dependability), the ability of not having an unwanted operation (security) and the ability of not having an incorrect operation (reliability). The reliability is the combined ability of not having a failure to operate and of not having an unwanted operation. These indices are defined as follows:

Dependability:

$$D = \frac{N_c}{N_c + N_f} \quad (1)$$

Security:

$$S = \frac{N_c}{N_c + N_u} \quad (2)$$

Reliability:

$$R = \frac{N_c}{N_c + (N_f + N_u)} \quad (3)$$

where

N_c = number of correct operations
N_f = number of failures to operate (missing operations)
N_u = number of unwanted operations

The reliability (R) of a protection system is the probability that a protection can perform a required function under given conditions for a given time interval.

Statnett has since 1999 been recording all protection responses at the levels 132 – 420 kV, comprising correct and incorrect operations. The performance indices (1) – (3) are calculated for the two years 1999 and 2000 and shown in Table 2 below. The number of protection responses and failures are shown in Table 1.

The large number of responses of the 220 - 420 kV line protection is due to the fact that the protection is duplicated at the levels 220 – 420 kV in Norway.

TABLE 1 Number of protection responses 1999 - 2000

Protection	Total	Unwanted	Missing
132 kV line	673	49	15
220-420 kV line	1110	78	40
132 – 420 kV transformer	302	101	4

TABLE 2 Performance indicators 1999 – 2000

Protection	Dependability	Security	Reliability
132 kV line	0,978	0,926	0,905
220 – 420 kV line	0,964	0,927	0,894
132 – 420 kV transf.	0,987	0,661	0,652

The dependability is high (>0,96) for both line and transformer protection. It is a bit lower for 220 - 420 kV lines than for 132 kV lines and transformers. The security is lower than the dependability, although quite high (>0,92) for line protection. 220 - 420 kV line protection has a bit lower reliability than 132 kV line protection. On the other hand, the incorrect operations of protection for 132 kV lines has resulted in far more ENS than protection for 220 – 420 kV lines in 1999 – 2000: 542 MWh compared to 81 MWh in sum for the two years. The 132 kV network has a simpler topology and covers larger areas.

The security of transformer protection is however very low compared to the line protection. This is due to the large number of unwanted operations of the transformer protection in 1999 – 2000. About 38 % of the total number of responses was unwanted. For the differential transformer protection more than half the responses are incorrect, and the security is calculated to 0,49. The main causes for these unwanted operations are found in the groups “design, installation etc” (31 %) and “technical” (22 %). Incorrect operation of transformer protection resulted in a sum of 800 MWh ENS for 1999 – 2000 (about 300 MWh was caused by one incident). This corresponds to 56 % of ENS caused by protection system failures at the voltage levels 132 – 420 kV in 1999 – 2000. P&C line and transformer operation failures resulted together in 21,5 % of the total ENS at these levels (compared to about 17 % in the period 1990 – 1999). Unwanted operation amounts to 65 % of the ENS in 1999 - 2000. The rest is missing (31 %) and delayed (4 %) operation.

Using the data of protection responses for the two years 1999 – 2000 we can calculate the reliability of the numerical distance protection versus the conventional units. It has been a total of 1124 responses of the conventional distance protection 132 – 420 kV these years and 434 responses of the numerical devices. For both types about 10 % of the total number of responses have been incorrect operations. The performance indicators are shown in Table 3.

TABLE 3 Performance indicators for distance protection 132 – 420 kV 1999 – 2000

Protection	Dependability	Security	Reliability
Conventional	0,980	0,926	0,907
Numerical	0,961	0,942	0,906

These results illustrate that the dependability of the numerical devices is lower than for the conventional units, while the security is higher. The experiences so far have shown that there have been mostly human failures on the numerical devices (Fig 4). These are operation faults and incorrect settings (while putting into operation). The numerical protection is quite recently put into operation and the failure frequency will hopefully decrease with increasing competence in the use of the new technology.

The numerical devices can be provided by self-monitoring. It can be argued that this ought to lead to fewer unwanted operations as the maintenance intervals may be increased and the self-monitoring reduces the need for duplication of the protection system. However, the self-monitoring will not discover all types of protection system failures. The two years of statistics is also a too short period to make certain conclusions about the reliability of the protection technology.

4. MEANS TO IMPROVE THE PERFORMANCE

In this section we will focus on different measures to improve the performance of the protection and control system. How is it possible to improve the performance, reduce the CENS costs and improve the quality of supply? Protection performance strategies and design criteria for the bulk transmission 300 – 420 kV are discussed in [6]. How to utilise the integrated numerical devices in a cost-effective way is discussed in [7, 8] as well as protection and local control design in substations. In the further work it is important to consider the substations and the network from distribution to the bulk transmission as a whole. In this section topics for further work and possible measures for improvement of protection system performance and quality of supply are discussed. The measures may cover substations and different network levels to a varying degree.

Evaluation of the equipment's condition
There is some ill-conditioned P&C equipment around in the power system and many network companies do not have an overview over the equipment's condition. Methods to evaluate and control equipment conditions will be a good investment.

Plans for protection system performance
One important reason for incorrect operations of P&C at the lower network levels, is the lack of plans describing how the system should perform during a fault (protection plan). A protection plan includes

- Detailed calculations of the power system during normal and fault conditions.
- Evaluation of the principles on how the power system should perform under normal and fault situations.
- Accurate setting plans for the equipment at all voltage levels and all feeders in the network.

Further it is necessary to secure that the equipment in the station is in accordance with the planned values to obtain a good result.

Working procedures
A large part of the unwanted operations of P&C equipment comes from work done in the stations. The lack of plans for the practical work in the station can be an important reason. How can we change this? It is important to control the quality of the work procedures in such way that unwanted functions are avoided.

Reconnections in the network
When a person works in a station while the equipment is in operation, there may be a high possibility to cause an unwanted disconnection. The possibility and benefit of having reconnections or parallel connections while performing checking routines should be evaluated.

Fault analysis as basis for maintenance
Increasing the use of fault analysis could reduce the maintenance of P&C equipment and thereby reduce maintenance and CENS expenses. It is important to provide as much information as possible for this purpose. Today there is only a limited amount of information available from the control centres and from the fault recorders placed around in the system. Most of the bay units (P&C) in today's power systems do not have serial communications between the units and the control centres /relay offices. Fault analysis can be used as a control tool in relay plans and the principles we use about how the system should perform under fault conditions. A fault in the network is an "exam" for the "relay engineers" and the analysis of faults can uncover mistakes in our plans. In consequence, fault analysis can be used to improve the plans.

Numerical equipment gives new possibilities
Stations with numerical devices and communications provide higher possibilities to obtain relevant information when a fault occurs. This should have consequences for the operation and the maintainability of these stations. This is especially true for the monitoring of:

- Bay units (Protection, control and supervision)
- Communication between bay units (self-monitored)
- Tripping circuits (if a process bus is used between bay units and high voltage components)
- High voltage components
- Communication with other stations and control center

It is possible to use these amounts of information for everyday operations and in a system in which the fault analysis is an important part of the maintenance routines.

Self-monitoring system
Self-monitoring is assumed to increase the bay units' security, dependability and availability [7, 8]. The highest may be the influence on security (Eq (2)). Self-monitoring reduces the probability for unwanted operations because it is possible to restrain those incorrect operations completely or partially through associated signals. Self-monitoring may also increase the availability of P&C because of the reduction of the time required to detect a protection system failure. Compared with equipment without self-monitoring, where faults are discovered during routine controls, this is a dramatic improvement.

Increased automation
To reduce the time that a component is unavailable in the network (downtime), auto-reclosure of single components and automatic restoration of larger areas has become more important due to the focus on quality of supply (CENS). Personnel in the control centre will have a reduced possibility to take corrective action in the network within the critical time of for instance 3 minutes in the CENS arrangement. In most cases it will take longer time to follow the chain of events which includes updating of information to the control centre, updating of the situation to the operator, and finally the operator's decision and reaction. Because of this, a solution including automation at bay unit level or auto-restoration of larger areas will be a central subject. There are several advantages to commit to automation solutions, but the most important are:

- Reduction of interruption time
- Lower cost associated with CENS
- Lower probability of human error.

Controlled and uncontrolled auto-reclosing at different voltage levels has a long tradition in Norway. Typical for those systems in operation is that they are bay based. There are local solutions for auto-reclosure of single lines.

At the same time there are several 132/66 kV networks in Norway that have systems for automatic restoration. Automation solutions can be divided in stations with and without communication:

a) Stations without communication equipment
In stations without communication it may be recommendable to put the auto-reclosing equipment into operation. In radial networks downtime will be decisive and thus it will be important that reclosing happens within 3 minutes, i.e. the time before CENS starts to count. In meshed networks downtime is not critical, and thus it is important to focus on "fault extinguishing" without overlooking that also here auto-reclosing will be important in order to restore normal operation.

b) Stations with possibility for serial communication
The new numerical techniques with serial communication give larger possibilities for the exchange of information between stations and the control centre. The challenge is to use the new technology in a proper way.

It is the manufacturer's responsibility that users can exchange information between stations independently of manufacturer. As per today, serial communication between the control centre and the stations is a problem. This can also be true for station and control centre delivered by the same manufacturer, but it may be a larger problem in the case that these are delivered by different manufacturers. For many years there has been a discussion about protocols and possibilities for exchange of information. The possibilities available today limit the opportunities for system automatic restoration because of the limitations with the exchange of information. This problem should be solved as soon as possible.

The key is the knowledge and skills
It is our opinion that the key for the success within this area will be the level of skills and knowledge in this particular field. Revenue regulation of the network companies and focusing on the costs has partially caused a downsizing of expertise in P&C and partially a postponement of the needed investment. It is little realistic that we turn back to a system in which the skills about almost anything are spread all over the company. However the companies should have the necessary general skills to be able to identify the problems, evaluate the needs and implement the necessary measures.

5. CONCLUSIONS AND FURTHER WORK

In this paper we have presented results from ten years of statistics of protection system failures. The results cover the voltage levels 33 – 420 kV. The majority of protection system failures are unwanted operations. About half the unwanted operations are caused by human activities during operation of the power system, or related to testing and setting of the P&C. Protection system failures are also large contributors to energy not supplied to end-users. Incorrect operation of protection and control counts for about 17 % of the ENS due to fault outages at the levels 33 – 420 kV.

Examples of performance indicators (defined by CIGRE) are given for the two years 1990 – 2000. The dependability is quite high both for line and transformer protection, while the security of transformer protection is low. The results also illustrate that the dependability of the numerical devices is a bit lower than for the conventional devices, while the security is higher. However, two years of statistics is a too short period to make certain conclusions about the reliability of the protection system.

Finally the paper presents some topics for further discussion related to improvements of protection system performance and quality of supply to end-users.

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