Abstract – This paper discusses analyses of power system instability due to relay failures related to grid faults. Different power systems differ significantly in their response to a disturbance and in their behavior in disturbed conditions. Therefore, the vulnerability of the system also to relay misoperations is highly case-dependent. When stability is the issue, a system breakdown most probably occurs when fault duration is extended or when several components trip unselectively, which both can lead to an unstable condition. When considering the method for evaluating the power system consequences of disturbances, a steady-state approach is not sufficient for systems limited by dynamic stability criteria. In these cases, system wide dynamic simulations are needed. This paper describes the dynamic simulations of the Nordic power system after relay failures and concludes that the frequency of a system breakdown differs significantly according to the direction and amount of power transmission.

Keywords: security analysis, power system instability, relay failures, dynamic simulations

1 INTRODUCTION

The performance of the relay protection system is important for maintaining power system security. According to many papers, e.g. [1, 2], relay failures are in a key role in the processes that lead to a system breakdown. A term ‘hidden failure’ of a relay is presented for “a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event” [1]. Hidden failures remain hidden until their existence is exposed by a disturbance in the system. Because of the relation between the initial disturbance and the hidden relay failure, the probability may be higher than the probability of two independent simultaneous faults, and as a result the risk of a blackout may be larger than is normally anticipated in an N−1 operated system.

There has been research in cascading failures as a cause of a system breakdown in power systems. A cascading failure is defined as “a sequence of dependent failures of individual components that successively weakens the power system” [3]. The studies have modeled cascading failures as a process without power system simulations [4] or with load flow based approaches, which could include a statistical modeling of generator instability [5, 6]. A comprehensive review of methods and modeling approaches in cascading and blackout studies can be found at references [3, 7].

This paper concentrates on to analyze the impact of relay failures on system stability with dynamic simulations.

2 POWER SYSTEM CHARACTERISTICS

Power systems differ significantly in their response to a disturbance and in their behavior in disturbed conditions. Therefore, the vulnerability of the system also to relay misoperations is highly case-dependent. If the dynamic angle or voltage stability or damping of electromechanical oscillations set the limits to the transmission capacity, the maximum allowed power flows are in most cases lower than the maximum flows in systems where the thermal capacities of the lines define the maximum power transfer. When stability is the issue, a system breakdown most probably occurs when fault duration is extended or when several components trip unselectively, which both can lead to a dynamically unstable condition. If the transition to the post-fault state is stable, the remaining lines transmit more power but probably do not become thermally overloaded. In other words, in a dynamically limited system, cascading tripping due to line thermal overloading cannot be seen as a probable scenario causing a system breakdown.

When considering the method for evaluating the power system consequences of a relay failure, a steady-state approach is not sufficient for the systems limited by dynamic stability. In these cases, system wide dynamic simulations are needed.

3 THE FINNISH TRANSMISSION SYSTEM

The Finnish transmission grid is part of the Nordic synchronous power system (Figure 1). The Nordic transmission system consists of different areas with generation and consumption centers connected with long AC lines.
There are critical transmission cross-sections between Finland and Sweden (RAC) and between Northern and Southern parts of Finland (P1) (Figures 1 and 2). The shape of the area drawn by the transmission limits (Figure 2) shows that a large power flow from Northern Finland to Southern Finland is inevitably connected to a large import from Sweden and similarly a large power flow from Southern Finland to Northern Finland is connected to a large export to Sweden.

The Finnish main protection system of 400 kV lines consists most often of distance relays using a permissive overreach transfer trip (POTT) scheme. In the 400 kV grid, the line protection is redundant and consists of two separate main protection systems. In some cases, the other relay is a differential relay. In the 110 kV and 220 kV systems, the main protection relays and telecommunication channels are not duplicated. As a backup protection at all voltage levels, there are trips of the delayed zones of the distance relays, overcurrent relays, and earth fault relays for high resistance earth faults.
5 RELAY FAILURE DATA

5.1 Analyzing the data
The studied relay failure data is from the line protection of the Finnish 110 kV, 220 kV and 400 kV grids from 2000 to 2009. The studied data includes protection system failures that relate to grid disturbances and also relay failures that are detected with periodical testing or self-supervision of the protection devices. The failure data consists of date and time, faulty component, detection method (e.g. grid disturbance, self-supervision), type of incorrect operation (e.g. unselective trip, missing trip), cause of the fault, relay type (electromechanical, static, processor).

When studying the relay protection failures, we have made an assumption that 110 kV devices are basically similar with 220 kV and 400 kV devices, and the failures occur because of similar causes, and therefore the data from different voltage levels can be combined together.

We studied the data in order to find out the relative proportions of missing and unselective trips. An unselective trip here means an unwanted trip during a grid fault. A missing trip means that a relay fails to operate during a fault. Only failures of the main protection relays, line distance and differential relays, were included in the study. The number of missing and unselective operations was calculated for different relay classes: electromechanical, static and microprocessor relays. In addition, the most common causes and detection methods were found for different relay classes.

Unwanted spontaneous line trips without a grid fault, caused for example by a human error during relay testing, were not included because they are not really misoperations of the device. This exclusion is also what we suggest for calculating the reliability indices to the protection systems, because if we are interested in the performance of the protection systems rather than the quality of the relay testing. In this paper, the exclusion of the unwanted operations caused by testing can also be justified with the fact that a single line trip, especially without a grid fault, in an $N-1$ operated system will not cause system wide consequences.

The sum of device years is about 6000 and the number of relay misoperations is about 130 in the included failure data.

5.2 Observations
The first observation from the data is that most of the missing operations of the protection systems are revealed with tests or self-supervision signals and do not cause disturbances (Figure 3). Unselective operations, on the other hand, reveal themselves nearly always during disturbances and are not usually found during testing.

In the 10 year relay failure data there were no missing trips related to disturbances in the 400 kV relays. If at least one of the duplicated 400 kV relays trip, the statistics treat it as a successful operation since a trip signal exists. Therefore there may have been cases where other of the duplicated relays did not trip. In the 220 kV and 110 kV relays there were cases were the not duplicated main line protection relay had failed to operate. This result underlines the importance of redundancy in the most critical protection systems.

![Figure 3](image)

For different relay classes, the relative proportions of missing and unselective trips are significantly different as Figure 4 shows. In the data most of the detected misoperations of electromechanical relays are unselective trips, which is not the case with processor and static relays. Furthermore, the device years of different relay classes in the data seems to correlate better with the number of unselective trips than with the total number of observed misoperations. This is because modern relays send self-supervision signals, and some missing trips are detected because of this. Self-supervision cannot in most cases reveal relay failures that would lead to unselective trips, which means that self-supervision does not reduce the number of unselective trips, i.e. improve the performance in this respect.

![Figure 4](image)
6 ANALYSIS OF SYSTEM IMPACTS

6.1 Dynamic simulations

In our security studies [8,9], we have done dynamic simulations with a detailed grid model of the Nordic power system. The model consists of about 6000 buses and 1500 generators.

The simulations included a comprehensive selection of \( N - k \) faults, which here means a line fault followed by additional trips by the backup protection due to failures of instantaneous tripping procedure (Figure 5). In addition to backup protection after relay failures, also backup protection after stuck circuit breakers was simulated. A systematic analysis with 3-phase faults in every line (each line with three fault locations) was performed with similar protection system failures. The necessary steps for a successful line trip depend on fault location and busbar systems and protection system schemes.

![Success](image1)
![Failure](image2)

**Figure 5:** Example of an event tree describing different tripping procedures after a line fault [8]. The success and failure branches are: 1. Trip signal from the relays (line end 1), 2. Trip signal from the relays (line end 2), 3. Circuit breaker trip (line end 1), 4. Breaker failure relay (line end 1), 5. Circuit breaker trip (line end 2), 6. Breaker failure relay (line end 2). The end branches that represent the chains of events are simulated to determine the events leading to a system breakdown (SB) or remaining stable (OK).

The frequency of line faults and probabilities of different branches are used to calculate the frequencies of the end branches. Each end branch describes the fault duration and the tripped lines, which are necessary to know when simulating the transition to the post-fault state in order to find out if the system remains stable or not. The result of each simulation was either a system breakdown or no system breakdown. No other classifications were made. Fault and component failure frequencies give an average frequency of occurrence for every simulated chain of events.

6.2 Results

The simulation results for five different power flow cases show that the frequency of a system breakdown of studied failure sequences differs significantly according to the case (Figure 6). In all power flows, the line fault frequency and relay failure probabilities were the same. The five power flow cases represent different operational situations and power flows in critical cross-sections RAC and P1 in Figures 1 and 2 [9]. Figure 6 clearly shows that the amplitude and direction of power flows in critical cross-sections influences the probability of a system breakdown.

The system breakdowns were mostly caused by transient instability of large generators. This is a different fault consequence than in normal \( N - 1 \) contingencies, where most often the reason is voltage stability or the lack of damping of electromechanical oscillations.

If we classify the simulation results according to the number of tripped lines, we see that chains of events with one or three lines tripped are most probably the cause of the system breakdown. In all of the studied chains of events, the fault duration is extended, which explains the system breakdown connected to a trip of single line. In the case of three lines tripped similar conclusions cannot be made because at least some of the events could also lead to a system breakdown without the long fault duration. The chains of events with two, four or five lines tripped are with relatively small proportions of the system breakdown frequency.

![The number of tripped lines](image3)

**Figure 6:** System breakdown frequencies (1/year) in the studied cases classified according to tripped lines. Case 3 has large export and Case 5 maximum export to Sweden (RAC). Case 4 has large import (RAC). Cases 1 and 2 have small power transfers (RAC, P1). Case 1 has more generators connected to the system than Case 2.

The share of such chains of events (of the simulated events) that lead to a system breakdown increases with the number of lines disconnected in the fault sequence (Figure 7). What affects this significantly is that in the studied chains of events, the fault durations are also extended when several lines are tripped. This is because if there is a missing operation of the protection system, there is always a delay before the backup protection system operates, and additional components are tripped. For example, almost all of the chains of events that lead
to a system breakdown with five lines tripped have fault
duration of one second (zone 3 of the distance relay).

Important observation is that about 80% of the studied
events with two lines tripped and about half of the
cases with four or five lines tripped do not cause a sys-
tem breakdown even in the most unstable case. This tells
that an \( N-1 \) operated system can withstand discon-
nections of several less critical lines.

The chains of events that lead to the tripping of sev-
eral components are usually less probable, and therefore
cause less of the system breakdown risk (Figure 6), even
though relatively more of these chains events may cause
a system breakdown (Figure 7).

7 DISCUSSION

In this paper we have studied the vulnerability of the
transmission system to relay failures, both missing and
unselective trips.

When considering the impacts of relay failures on the
risks of a system breakdown, there are two aspects that
need to be evaluated: the consequence and probability.
The consequences of relay misoperations are highly
dependent on the system. If the system is operated close
to thermal \( N-1 \) limits of the lines, an unselective line
can lead to line overloading and cascading tripping.
However, if the system is not usually highly loaded or
transmission limits are significantly lower than thermal
limits due to dynamic stability criteria, the trip of one
extra line when clearing a fault is not a similar threat to
this system.

According to the studied relay failure data, unselective
trips are significantly more common than missing
trips, especially in case of redundant protection systems.
On the other hand, missing trips may have significantly
bigger consequences since after a missing trip the back-
up protection trips several components with a delay. The
tripping of several components is a risk in every system
operated at \( N-1 \). In addition, a delayed trip jeopardizes
the security if the system is dynamically limited and the
loss of stability is a significant risk. Also the loss of
stability may be a very fast phenomenon and therefore
remedial actions after the initiating event may be im-
possible or at least difficult to perform.

System properties, for example the constraints that
set the limits to maximum power transfer, the direction
and amplitude of power flows, transient stability after
extended fault durations, and the number of tripped
components, affect the power system response to faults
connected with relay failures. Also fault location affects
the consequences; faults with extended clearing times
near big generators can lead to transient instability and
to a system breakdown.

One observation from the relay failure data was that
there were no detected missing trips related to distur-
bances in the main 400 kV line protection, which was
explained with redundant relays. Important in case of
duplicated relays is to eliminate the possible sources of
common cause failures. This can be done by selecting
relays from different manufacturers or at least demand-
ing that the duplicated relays have to be different types.

In case of the processor relays the latter might not be
sufficient because the same software might be used even
if the devices are not the same type.

From the relay failure data we saw that more missing
trips are detected in case of modern relays with self-
supervision capabilities. The question is that does this
mean there will be less missing trips during disturbances
when all the electromechanical relays are replaced with
modern processor relays, or are we detecting more
missing trips because processor relays have, in addition
to self-supervision capabilities, more malfunctioning
capabilities compared with electromechanical relays.

8 CONCLUSION

Misoperations of the relay protection jeopardize the
stability and security of a power system. Both missing
and unselective trips lead to disconnection(s) of addi-
tional component(s), but missing trips also lead to ex-
tended fault duration. When several components trip,
there is a risk of a system breakdown for all \( N-1 \) oper-
ated systems. If the stability sets the \( N-1 \) limits for
maximum transmission, extended fault duration may
lead to an unstable situation and a system breakdown
even in cases when only one line trips too slowly. How-
ever, an \( N-1 \) operated system can often withstand dis-
connections of several less critical lines.

A system breakdown due to the loss of stability might
occur almost instantaneously and might be impossible to
perform any responsive actions by the control center
personnel or automatic load shedding after the initiating
event. Therefore it is crucial that the possible chains of
events that can lead to the loss of stability have been
analyzed properly and the mechanics behind the system
breakdown are revealed.

The grid simulations of the Finnish power system
show that the probability of a system breakdown varies
according to the amplitude and direction of power flow
across the critical cross-sections. When the power flow
from South to North in Finland and from Finland to
Sweden is high, the system faces more frequently a
system breakdown after similar fault location and relay misoperations than in cases when the power flow is low or to other direction. The cause of the system breakdown was typically transient instability of big generators due to extended fault duration.

Redundancy of the main protection relays, regular relay testing, and self-supervision of relays reduce the number of missing trips of the protection system in disturbances. There are no as effective means to avoid unselective trips during grid faults even though occasionally relay tests may reveal failures of this kind.

REFERENCES