A METHOD FOR ANALYSING THE EFFECT OF SUBSTATION FAILURES ON POWER SYSTEM RELIABILITY

Liisa Pottonen
Fingrid Oyj
Helsinki, Finland
liisa.pottonen@fingrid.fi, liisa.pottonen@tkk.fi

Urho Pulkkinen, VTT Industrial Automation
Mikko Koskinen, Jussi Jyrinsalo, Fingrid Oyj

Abstract – The paper describes a probabilistic method for transmission grid security evaluation. The most efficient contributions to the system reliability can be found with the probabilistic methods. The method uses event and fault trees and combines them with power system dynamic simulations. Event trees model the substation protection and trip operations after line faults. Different event tree end states (fault duration, circuit breaker trips) are simulated with power system dynamic analysis program. The dynamic analysis results are classified into secure, alert, emergency and system breakdown. Also a special alert state 'partial system breakdown' was classified. After that the event trees are analysed again, but now the end branches are labelled according to the power system states. The probabilities, minimal cut sets and grid level impor-tance measures (Fussell-Vesely, risk increase and decrease factors) are calculated for the total and partial system breakdown. In this way the relative importance of the substation components regarding to the total and partial system breakdown was reached. Also the more and less likely contributing factors to system breakdown were re-ceived. With this method, an existing 400 kV transmission grid with its line fault and device failure statistics was analysed.

Keywords: substation, protection, failure, reliability, power system, importance

1 INTRODUCTION

The traditional way to plan and operate a power system is the deterministic n-1 criterion. In this method the power system shall be operated in such a way that after any single contingency the system remains stable and a new operating point without overloading and voltage violations can be reached. Probabilities of different faults are not traditionally taken into account; instead all faults that may limit the transmission capacity are treated equally. This traditional method can lead to conservative utilisation of the grid. However, the most efficient contributions to the system reliability enhancement can be found by using the probabilistic rather than deterministic methods.

The power systems are usually large, complex and in many ways non-linear. The post-fault phenomena in a power system are dynamic in nature and dependent on the grid connection and load flow situations in different parts of the grid. Thus the security analysis of a power system is a difficult task. The effects of an unreliable power system transmission can be widespread and affect millions of people. The traditional way to do the transmission grid security analyses is to assume that post-fault substation events (the protection system and circuit breaker operations) are 100 % reliable, i.e. to not take into account the possible component failures at all. In the literature, if the power system security is studied with a substation model, the grid model presented is often very simple compared to real grids [1], [2].

There have been many security analysis studies made without a substation model in which correct trips after disturbances occur and the interest is the power system state after those trips [3], [4], [5], [6], [7], [8], and [9]. This assumption is good for operation planning purposes, but has limited use as part of an overall approach to the reliability analysis of transmission grids.

Miki et al. [10] have developed a hybrid model that includes both power system dynamic simulations and event trees for the protection. The method is applied to a small grid. Since only the protection is modelled, the authors do not take into account the failures of the circuit breakers.

Many authors deal with the reliability of protection but pay no or little attention to the consequences of protection failures to the power system, [11], [12], [13], [14], [15], and [16].

In this paper we briefly present a method for transmission grid reliability estimation in such a way that both the post-fault substation events and the power system dynamics are included. The method is applied to a real 400 kV transmission grid. It takes into account the substation busbar schemes, protection systems used, component failure probabilities and the effect of substation operation failures on the power system dynamics. Importance measures for the substation components of the whole Finnish 400 kV transmission grid for system breakdown and total system breakdown are calculated, too. A more detailed presentation of this model can be found in [17].

The reliability and risk assessment tools have widely been used for many applications, e.g. for nuclear power plants. There are several software tools for these purposes. The purpose of this study was also to evaluate how applicable the traditional reliability methods, such as failure mode and effect analysis and event and fault trees, are for power system reliability analysis. Mathematical modelling and computational methods are the tools used in this research. The reliability analysis for substation component operations and dynamic simulations for the power system are made and combined in order to obtain the objectives of the study.

The outline of the paper is such that first the reliability concepts used in this study are introduced. The statistics of the grid faults of the Finnish 400 kV transmission system are presented. The Finnish 400 kV line protec-tion system is briefly described. After that the combina-tion of the substation reliability analysis model and the dynamic simulations is presented. Finally some results and conclusions are reported.

2 LIST OF ACRONYMS

BFR	Breaker failure relay
CB	Circuit breaker
D	Differential (relay)
FMEA	Failure mode and effect analysis
FV	Fussell-Vesely's measure of importance
HVDC	High voltage direct current
MCB	Miniature circuit breaker
MCS	Minimal cut set
POTT	Permissive overreach transfer trip scheme
PSB	Partial system breakdown
RAR	Rapid automatic reclosing
RDF	Risk decrease factor
RIF	Risk increase factor
SB	System breakdown
Z	Distance (relay)

3 RELIABILITY CONCEPTS

3.1 Power system reliability

Reliability of a power system is a general term that refers to the probability of its satisfactory operation in the long term, whereas the power system security is the ability of the power system to withstand disturbances arising from faults or unscheduled loss of power system supply equipment(s). The distinction between reliability and security is worth noticing. Reliability is a function of the time-average performance of a power system, in different loading situations, after different faults, during different outages. It can only be judged by consideration of the system’s behaviour over an appreciable period of time. The security on the other hand is a time-varying attribute, which can be judged by studying the performance of the power system under a particular set of conditions. To be reliable, the power system must be secure most of the time [18].

3.2 General reliability concepts

Event tree is a logic tree diagram that systematically describes the sequence of events, which most often are safety functions planned for preventing a catastrophe. The diagram starts with an initiating event (in this case a line fault) and provides a systematic analysis of the different possible outcomes of the sequences. Event tree analysis can be quantitative, qualitative or both.

Fault tree is a logical model, which explains the failures of higher level as a logical function of lower level failure events. Higher level in this context means the system and lower level means the subsystems and components. In a fault tree construction the starting point is the specified system failure. The system components are called as basic events in a fault tree.

A cut set is a set of basic events whose simultaneous occurrence ensures that the top event occurs that cannot be reduced. A cut set is a minimal cut set if it can not be reduced. Both a fault tree and event tree analysis produces a group of minimal cut sets.

Fussell-Vesely’s measure of importance FV(i) of a basic event i is the approximate conditional probability that at least one minimal cut set that contains component i is failed, given that the system is failed. A minimal cut set is failed when all the components in the minimal cut set are failed. Thus the Fussell-Vesely importance identifies the components that have the largest probability of being the cause of the system failure [19].

Risk increase factor (RIF) is the ratio of the conditional system unreliability if component *i* is not present (or if component *i* is always failed) with the actual system unreliability. It indicates the importance of maintaining the current level of reliability for the component. Risk decrease factor RDF is the ratio of the actual system unreliability with the conditional system unreliability if component *i* is replaced by a perfect component. The risk decrease factor identifies the basic event that would improve the system most if it would be perfectly reliable [19].

The Fussell-Vesely importance is directly proportional to the unavailability of the component. Thus FV importance measures could be used alone for identifying the potential components for safety improvement. FV importance is comparable to risk decrease factor. The risk increase factor measure sees the system from the different point of view. RIF does not represent the component itself but the defence of the rest of the installation against a failure of a component [20].

4 STATISTICS OF GRID FAULTS

The system under study is the Finnish 400 kV grid. There have been 214 line shunt faults (48 short circuits and 166 earth faults) in the Finnish 400 kV grid during the years 1983-2002. Only 25 faults were permanent. The causes for line short circuits were a lightning stroke, a tree, forest fire, high wind, a fallen tower and a small aeroplane that cut the earth wires. The causes of earth faults were a tower or tower part failure, a vehicle that cut the guy of a guyed tower, ice on phase wires or dew on earthing wires, a tree and earth slide due to a nearby dumping place caused one tower to move. Some faults remained unknown. A current transformer has exploded nine times. The result of these explosions was the trip of a line, trip of a busbar or trip of two busbars. Only two

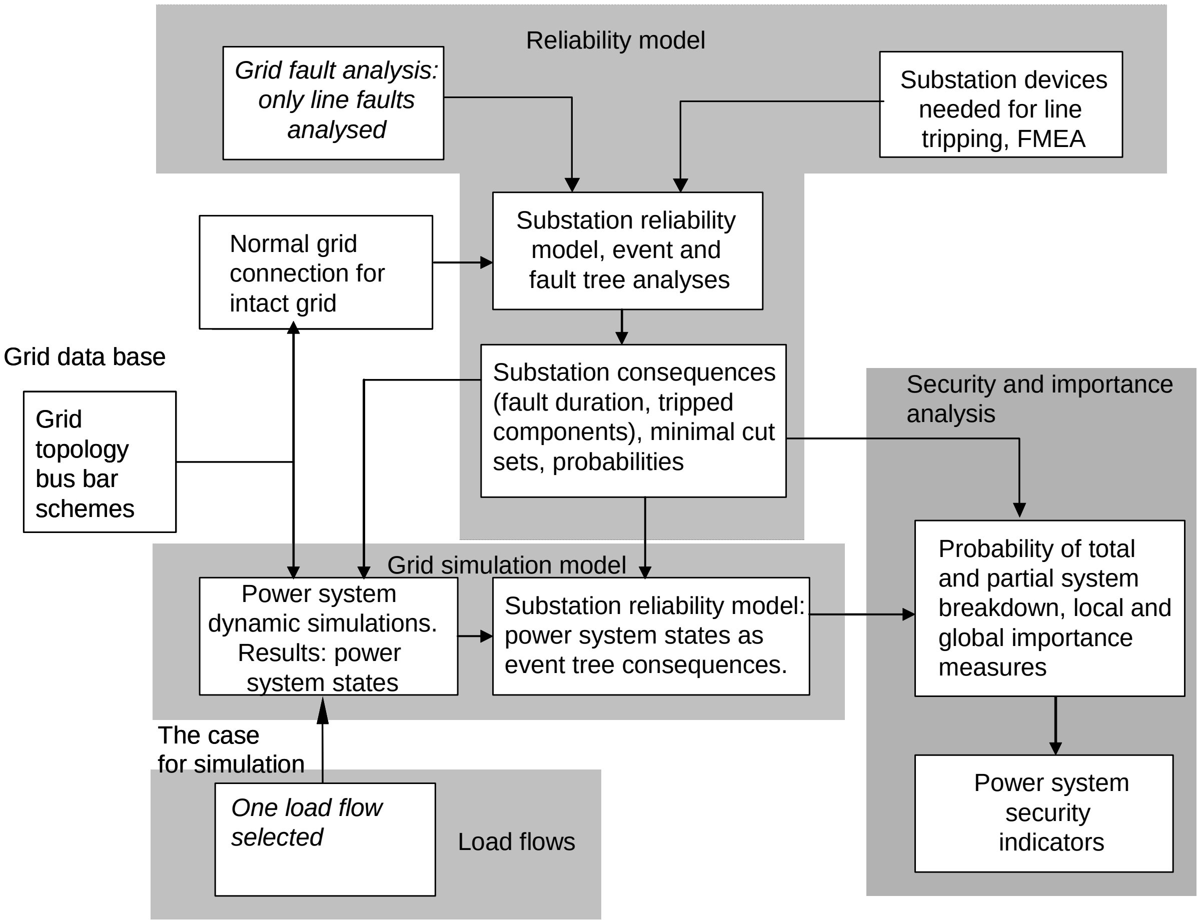

Figure 1: The block diagram of the reliability model. FMEA = failure mode and effect analysis.

busbar shunt faults were caused by some other reason than the current transformer.

This study deals with the line shunt faults and the substation events after the faults, since the line faults are the most common grid fault type.

The average annual line fault frequency used in this study is calculated from the 20 years statistics of Fingrid Oyj and it includes both the earth faults and short circuits. The estimate for annual line fault frequency per kilometre is 2.9E-03 (214 faults / 72800 km). It is the total number of line faults divided by the total line kilometre years. With 4300 line kilometres the average annual number of line shunt faults in the Finnish 400 kV grid is about 13.

5 THE FINNISH 400 KV LINE PROTECTION SYSTEM

The Finnish 400 kV transmission line protection system always consists of two separate main protection relays. The two main relays are most often different types of distance (Z) relays, which are equipped with permissive overreach transfer trip scheme (POTT) in order to trip instantaneously the faults near the line ends. POTT scheme needs a telecommunication channel. Very short lines and some other special lines, such as series compensated lines, are provided with one distance relay and one differential (D) relay.

Rapid automatic reclosing relays (RAR) close the circuit breakers after instantaneous line trips. One line end, which is called as a master, does the automatic reclosing after a time delay (usually 400 ms) if the line is dead and the busbar voltage is 400 kV. The other line end, which is called as a follower, makes the automatic reclosing if the line and busbar voltages are equal and the angle difference between them is small enough after a time delay, which is usually 600 ms.

The new installations of two main relays are redundant. They are situated in different relay cubicles, fed by different 220 V dc batteries and fed by different secondary coils of the instrument transformers. The two distance relays of the same line end shall not be of similar type. Therefore it is considered that common cause failure mode can be neglected with new installations. The old installations with electromechanical distance relays have a common miniature circuit breaker of the voltage transformer, which is modelled in the fault trees. The line protection system for 400 kV lines is equipped with one or two telecommunication channels. If there are two channels, they always have different routes and are redundant apart from the 48 V dc supply for the telecommunication devices.

The breaker failure relay (BFR) measures the current of the circuit breaker (CB) that has received a trip signal. If the current does not stop in a given time, the breaker failure relay trips all the circuit breakers connected to the same busbar as the faulted one and sends a trip signal to the distance relays at the remote end substation of the faulted line bay.

6 THE RELIABILITY ANALYSIS MODEL

The overall block diagram of the reliability analysis model presented in this paper is shown in Fig. 1. The reliability model includes the analysis of the initiating events (grid faults), substation model, dynamic simulations of the grid and both local and grid level importance analysis.

The substation reliability model is created with event and fault trees. Event tree analysis results are the different possible fault durations and circuit breaker trips. Also the probability of the consequences and corresponding minimal cut sets are received. These are called as substation consequences, and they are not dependent on the load flow or on the grid connection. The substation consequences are needed for power system simulation. The substation model takes into account all the devices that are needed for fault isolation, i.e. the protection system, the circuit breakers and the telecommunication channels.

Substation consequences were simulated with power system dynamic simulation software. The dynamic simulations were made only with one load flow and with a normal intact grid connection. The stability and the possible voltage and thermal limit violations and the reach of the remote back-up distance protection were checked for defining the power system post-fault state.

The effects of the substation failures to the power system are known after the dynamic simulations are analysed. The classification of simulation results is made according to power system states: secure, alert, emergency and system breakdown. Also a special alert case, called as partial system breakdown is introduced.

After the simulations are classified the power system states with respect to different substation consequences are known at one load flow; now they can be added as power system consequences to the event trees. When the event trees are analysed again, the results are the probabilities of different power system states after each line fault. Also minimal cut sets and importance measures for power system consequences can be calculated.

7 THE RELIABILITY MODEL OF A SUBSTATION

7.1 Event trees

Substation risk modelling follows the principles of Probabilistic Safety Assessment (PSA) and uses event and fault trees. PSA is originally used for safety analysis of nuclear power plants. This approach is suitable also for modelling the power system protection, since the method is developed for analysing the safety functions after an accident. The purpose in this study was to combine reliability modelling and grid analysis. Event and fault tree analysis is illustrative and the event trees, when correctly built, give the data needed for power system dynamic simulation. Here the event and fault trees are created and analysed by using commercial software for reliability and risk analysis. In this model each event tree branch always has one success and one failure path. A location, where one can create branches in an event tree, is called as a function event in the program used. The input values of the function events are calculated with fault trees; therefore the fault tree top gates are the inputs of the function events. An example of an event tree is presented in Fig. 2.

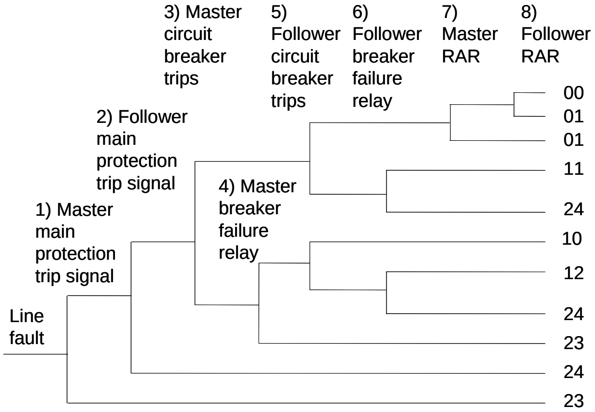

Figure 2: The event tree for substation events after a line fault. RAR = rapid automatic reclosing.

Because the distance protection operates in different ways in different fault locations, each line is divided into three sections. At the 20 % section near the master line end the distance relays at the master line end trip at zone 1 and the distance relays at the follower line end trip at permissive overreach transfer trip (POTT) scheme. At the 20 % section near the follower line end the follower relays trip at zone 1 and the master relays trip at POTT scheme. The faults at the remaining 60 % of the line length are tripped at zone 1 at both line ends. Therefore three event trees for each line are needed.

There are four different line types, when the number of circuit breakers (CB) is considered. The different line types are the following:

(1) Both line ends have double circuit breakers.
(2) The master line end has double CBs and the follower line end has single CB.
(3) The follower line end has double CBs and the master line end has single CB.
(4) Both line ends have single CBs.

Therefore twelve different event tree constructions are needed in order to model all the lines. The function events of the event trees and the numbers of different substation consequences of the event tree are marked in Fig. 2 with numbers. The explanations of the substation consequence identifications are listed here:

- 00 Both the protection and CBs succeed. Rapid automatic reclosure succeeds at both line ends.
- 01 Both the protection and CBs succeed. Rapid automatic reclosure fails at one or both line ends.

- 10 At the follower line end the protection and CB succeeds to trip the fault. At the master line end the CB fails to trip but the BFR protection succeeds to trip the busbar.
- 11 At the master line end the protection and CB succeed to trip the fault. At the follower line end the CB fails to trip, but the BFR succeeds to trip the busbar.
- 12 The relays at both line ends send trip signals, the CBs at both line ends fail to trip but both BFR protection systems succeed to trip the relevant busbars.
- 23 At the follower line end the protection and CB succeeds to trip the fault. At the master line end either the relays fail to send a trip signal or the CBs and BFR protection fail. The fault current continues to flow from the master line end.
- 24 At the master line end the protection and circuit breakers succeed to trip the fault. At the follower line end either the relays fail to send a trip signal or the CBs and BFR protection fail. The fault current continues to flow from the follower line end.

In the event tree construction it is worth noting that there exist fatal failures after which the failure branch always is the end branch. Such fatal failures are the substation consequences 23 and 24, where the fault current continues to flow at one line end. The probability that there would be no trip at one line end and simultaneously some failure at the other line end is considered to be so small that it was ignored.

7.2 Fault trees

The function events of the event trees need an input in order to calculate the branch probabilities. Fault tree top gates are used as inputs for event tree branches. An example of a fault tree is in Fig. 3. The top gate of this fault tree is the failure of two microprocessor distance relays to send a trip signal to the circuit breakers.

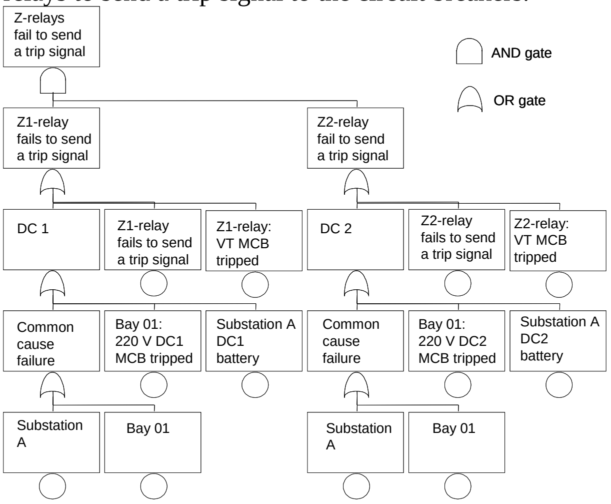

Figure 3: A fault tree, where the top gate is “two main protection distance relays fail to send a zone 1 trip signal to circuit breaker trip coils. Z = distance relay, MCB = miniature circuit breaker, VT = voltage transformer, DC = direct current.

The input data needed for quantitative fault tree analysis is received with failure mode and effect analysis, FMEA. The reliability model is created in order to analyse a real 400 kV grid. Thus the failure data as well as the structures modelled are specific rather than universal. Different transmission companies may have different substation structures, different protection systems, different maintenance policies and they have devices manufactures by different companies. The statistics presented in this chapter is received mostly from device failure database of the Finnish transmission system operator Fingrid Oyj. Some data is received from the supervisory control and data acquisition system. The data used in this research cover the different periods depending on the respective substation devices. The quality of data was not constant, being better for some components than for others. Also the experts of the maintenance, planning and local operation were interviewed during the FMEA process. The model does not contain other common cause failures than the substation and the bay.

8 POWER SYSTEM SIMULATIONS

The grid simulations were made by using a power system analysis software package. The grid model in the software was the Nordic interconnected system, but the grid models of other Nordic countries were not as detailed as that of Finland. The load flow used in the simulations was such that the power imports from Sweden and from Russia to Finland were roughly the half of the maximum allowed. The load flow used was a real load flow on a day in January 2002.

The other substation consequences were simulated exactly as they were defined in the event trees (fault duration and tripped components) except consequences 23 and 24. The consequences 23 and 24 (‘no trip at the substation’) were simulated in such a way that the fault duration was at one line end was 1000 ms after which the whole substation was tripped. This fault sequence modelled the case in which the remote back up protection trips the substation after the trip of the faulted line fails. The remote back up protection consists of the zone 2 of the distance relays.

The simulation results were classified to secure, alert, emergency and system breakdown. The system breakdown could be caused due to different causes. An unstable case in the dynamic simulations was one reason. Another possibility for a case to be classified as a system breakdown was such that the zone 3 of the remote back-up protection did not reach to fault location in consequences 23 and 24. In this case it did not matter if the dynamic simulation result was unstable or not. If there was no trip at the faulted line end and additionally, if the remote back-up protection did not reach to the fault, nothing else would isolate the fault.

An extra class ‘partial system breakdown’, which is a special case among alert cases, was used as well. The definition for a partial system breakdown is that it is an alert or an emergency state in which one or several extra generators or HVDC links trip due to the extended fault duration. It is worth noticing that if a radial line between a generator and the grid is tripped, this is not regarded as an extra trip, since the generator acts as planned after such a fault.

9 COMBINATION OF EVENT TREE MODEL AND THE SIMULATIONS

Fig. 4 presents the block diagram of the combination of the reliability model and dynamic simulations of the power system. After the dynamic simulations the new power system consequences received from power system simulations are added into the end branches of the event trees. Always when a substation consequence (e.g. a consequence numbered as 12 or 23) of a certain event tree leads to a total or partial system breakdown, the power system consequences SB for system breakdown and PSB for partial system breakdown are added to corresponding end branches of the event trees.

Figure 4 presents an example of an event tree with added power system consequence analysis results. In this case the power system state is a system breakdown if the follower or master line end trip is totally missing due to protection failure or due to the breaker failure protection failure.

After the power system consequences received from dynamic simulations were added to the end branches of the event trees of all lines, the consequence analysis of the system breakdown and partial system breakdown for the whole grid could be made.

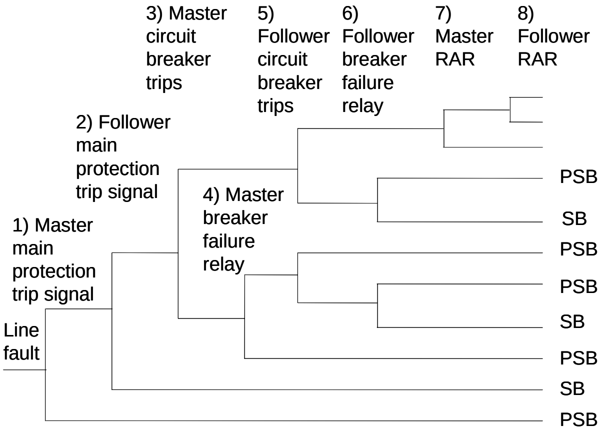

Figure 4: An event tree with the power system consequences system breakdown (SB) and partial system breakdown (PSB) added to the end branches. RAR = rapid automatic reclosing.

The event trees were now analysed again, but the goal this time is to ascertain the grid-level frequency of system breakdown and partial system breakdown and the corresponding importance measures. The probability, minimal cut sets and importance measures were calculated directly for power system consequences instead of substation consequences. The consequence analysis results are therefore at the grid level.

When calculating the contribution of one line to the power system, the initiating event frequency needs to be calculated. All the event tree analyses are made in such a way that the initiating event has a certain frequency. The results of the event tree analysis are therefore frequencies rather than probabilities. In this study, the initiating events are the line faults and it is assumed that the annual line fault frequency per line length is constant. The initiating event frequency therefore depends on the line fault frequency and on the line section length. The average line fault frequency estimate is calculated from the statistics of 20 years of Fingrid Oyj; it includes both earth faults and short circuits. The calculation of the line fault estimate is presented in Chapter 4.

The frequency of the system breakdown after line shunt faults is a result of the analysis of all event trees. The frequency of the system breakdown f(SB) is the sum of the system breakdowns of each event tree and is presented in Equation (1).

$$f(SB) = \sum_{M=1}^{K} f(SB_M) \qquad (1)$$

where $f(SB_M)$ is the system breakdown frequency of event tree M, f(SB) is the frequency of the system breakdown of all event trees and K is the number of all event trees in the model. Fig. 5 presents the block diagram of the combination of event tree analysis and grid dynamic simulations.

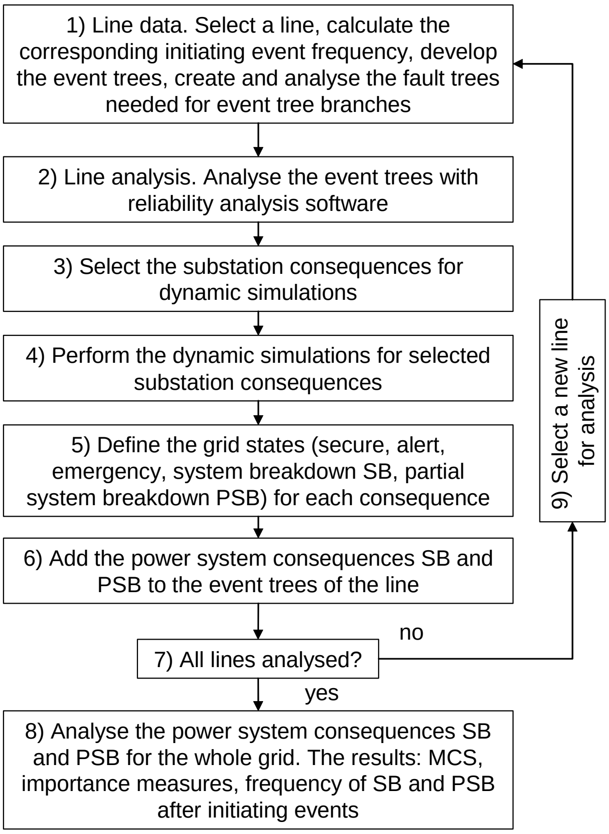

Figure 5: The block diagram of the power system reliability analysis after line faults.

10 RESULTS

The estimates of the partial and total system breakdown frequencies due to failures at the substation operations after all line shunt faults were calculated. The estimates were calculated for a lightly loaded grid only, which means that the values are to some extent too optimistic. The estimates for the time interval between successive system breakdowns and partial system breakdowns due to line faults were 730 years and 9 years, respectively.

10.1System breakdown

There were two different series of events that led to a system breakdown. The most common cause was the failure to trip at the substation, after which the remote back-up protection reach was not sufficient to isolate the fault. The substation consequences that caused this system breakdown were numbered as 23 or 24 and are presented in Section 7.1. This kind of series of events caused a system breakdown after faults at 26 of 39 lines. The system remained dynamically stable, but was classified as a system breakdown due to the insufficient reach of the remote back-up distance relays.

The other, and significantly less frequent, cause that resulted in a system breakdown was extended fault duration near the generators. The extended fault duration was caused by the circuit breakers that failed to trip or by the failure of the telecommunication channel that caused the trip signal delay. The extended fault duration in these cases was either 250 ms or 450 ms. This was the case after faults at 6 lines. If a circuit breaker fails, the fault duration is 250 ms and several lines are tripped at single circuit breaker substations. If the telecommunication fails, the faulted line is tripped after 450 ms, which also can lead to loss of transient stability of the system. Seven lines were such that there were no system breakdowns after the fault sequences studied.

There were 13963 different minimal cut sets that led to a system breakdown. Fig. 7 presents the components of the 100 most important minimal cut sets for the system breakdown. The frequency contributions of the cut sets are presented in Fig. 8. Those 100 minimal cut sets represent 81.1 % of the whole system breakdown frequency. It appears that minimal cut sets consisting of two circuit breaker failures represent more than half of the minimal cut sets. Both series of events that lead to the system breakdown are included.

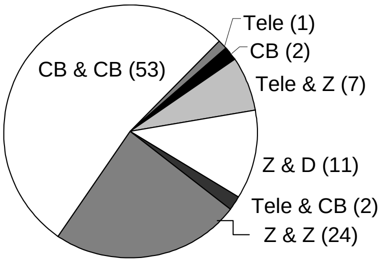

Figure 6: The components of the 100 most important minimal cut sets for a system breakdown.

The most important minimal cut sets for the failure to trip at the substation always have two components. These components are eit her two circuit breakers at the single circuit breaker substation, two main protection relays or the telecommunication of the main protection 1 and the relay of the main protection 2.

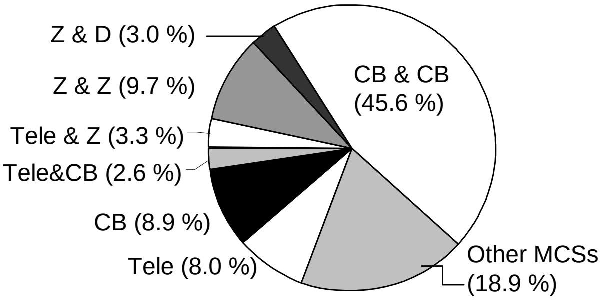

Figure 7: The frequency contributions of the 100 most important minimal cut sets for a system breakdown.

At a few fault locations the power system went into system breakdown due to transient stability. The minimal cut sets that are most important at grid level have one basic event only; it is either one circuit breaker or one telecommunication channel. These components were the highest in the minimal cut set ranking list and are ranked high in all importance measure lists, too.

10.1.1 Importance measures

Among the most important components according to Fussell-Vesely and risk decrease factor measures, there are 18 circuit breakers, 11 distance relays and 3 telecommunication channels. The FV measure of them varies between 0.11 and 0.13. Most, but not all, circuit breakers are air-blast circuit breakers. It is worth noticing that the remote back-up protection systems are not included in the importance measures, since they are not modelled in event trees.

The most significant RIF measures were different from Fussell-Vesely and risk decrease factors. The basic events for substations and bays had the highest RIF measure. This is natural, since the basic events for bays and substations are in all fault trees of that bay and that substation, respectively. Therefore they are in all function events of the event trees and their failure causes the system to fail. This is a structural property of the model.

In addition to this, all the voltage transformer miniature circuit breakers of electromechanical distance relays were ranked high in the list of grid-level RIF measures. The two electromechanical distance relays protecting the same line have a common miniature circuit breaker in the voltage transformer circuit. If the miniature circuit breaker trips, both relays are incapable of tripping the line.

The ranking list of local parameter sensitivity shows that the circuit breaker testing interval and the failure rate of air-blast circuit breakers are the parameters that have the highest sensitivity values. This list also has ranked quite highly some unavailability values of the distance relays.

10.2Partial system breakdown

A delayed line trip takes longer than 100 ms. A delayed trip was the reason for a partial system breakdown because of faults at 21 lines. The consequence of the delayed line trip was the trip of near-by generators or the permanent blocking of near-by HVDC links. One reason for the delayed trip was the failure of the telecommunication signal, which caused the distance relays to trip at zone 2. This caused the fault duration to be about 450 ms. The most important minimal cut sets of this power system state had only one basic event; this was the power line carrier telecommunication channel.

Another cause of a delayed trip is the circuit breaker becoming stuck. A breaker failure relay trips the other circuit breakers connected to the same busbar as the faulted circuit breaker. In this case, the fault duration was 250 ms. This failure caused the partial system breakdown on many lines near the generators and HVDC links.

There were 7603 different minimal cut sets that led to a partial system breakdown. The most important minimal cut sets with one component have a telecommunication channel or a circuit breaker. The frequency contributions of a telecommunication channel and a circuit breaker were 81 % and 19 %, respectively. The circuit breaker was often, but not always, an air-blast circuit breaker. Similarly, the telecommunication channel was often, but not always, a power line carrier. Naturally the components of these basic events were located near the generators or HVDC links.

10.2.1 Importance measures

Fussell-Vesely importance measures and RDF measures were identical to the list of minimal cut sets. The same circuit breakers and telecommunication channels that were ranked highest in the minimal cut set list were ranked high on the Fussell-Vesely and RDF lists, too. The reason is obvious: these components already have a high failure rate in the model.

When ranking RIF measures, it was the circuit breakers, substations, line bays and miniature circuit breakers of the voltage transformers that were ranked high. The circuit breakers were to some extent different from the ones with a high Fussell-Vesely ranking. Power line carrier telecommunication channels were not ranked very high in the RIF list.

The ranking list of local parameter sensitivity shows that the power line carrier telecommunication constant unavailability has the highest sensitivity for the partial system breakdown. The circuit breaker test interval has the second largest sensitivity.

11 CONCLUSIONS

This study deals with the transmission system reliability. More precisely, it proposes a reliability model for a power system, where the reliability of the substation protection and tripping functions after line shunt faults and the impact of possible failures of these functions on the power system dynamics are taken into account.

The main contribution of the study is a probabilistic method for transmission grid security analysis after line shunt faults. This method enables the estimation of the probability of the system breakdown and other power system states. The method developed for substation post-fault operations utilises event and fault trees and therefore it inherently brings the possibility to calculate different importance measures for substation components and for parameters of the model. In this study a method for scaling the local importance measures into grid level importance measures is developed. Importance measures can be used as tools for evaluating the importance of different grid components in several ways. With these importance measures, the more and less effective ways for improving the grid security can be found.

The method proposed is applicable to real transmission grids. Every line and every substation bay with the line protection primary and secondary components are included in the model. The basic functions in the substation operations after line faults are modelled, yet some simplifications and assumptions were made. The predefinitions and assumptions of the model were made bearing in mind the applicability of the method for the grids of real size. The second principle in the modelling process was the fact that the basic phenomena and reliability problems were of interest instead of every (local) detail.

It is important to remember the properties of a probabilistic approach. The probability indicates the degree of uncertainty and a result like ‘once in 9 years’ needs to be understood as a rational belief based on a certain case and certain assumptions instead of a scientific fact that can be proved. One has to bear in mind that we have modelled what we know about the transmission system. This probability model connects the evidence of the component reliability to the transmission system breakdown probability in a rational way.

The model gives information of the upper level (the transmission grid) reliability by using the reliability of the lower level components. There is no data available of the system breakdown but a lot of data about the failures of different components exist. The grid level failure is a function of the structural function of the system and the reliability of the system components. The important results in this approach are failure sequences that contribute to the system breakdown, the importance values and ranking of different components and the indicators for the system breakdown. Thus the main result is the knowledge of the system characteristics.

The model requires still development in order to be an everyday tool in a transmission company. After some development the method can be used for a security analysis in different grid connections and load flow cases.

12 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to TEKES, the National Technology Agency in Finland and to Fingrid Oyj for financial support of this research work.

REFERENCES

[1] Wu. F.F., Tsai, Y., Yu, Y. 1988. Probabilistic Steady-State and Dynamic Security Assessment. IEEE Transactions on Power Systems, Vol., No. 1, February 1988. Pp. 1-9.

[2] Loparo, K.A., Abdel-Malek, F. 1990. A Probabilistic Approach to Dynamic Power System Security. IEEE Transactions on Circuits and Systems, Vol. 37, No. 6, June 1990. Pp. 787-798.

[3] Aboreshaid, S., Billinton, R. 1999. A framework for incorporating voltage and transient stability considerations in well-being evaluation of composite power systems. Power Engineering Society Summer Meeting, 1999, IEEE, Volume 1, 18-22, Jul 1999. Pp. 219-224.

[4] Khan M.E. 1998. Bulk load point's reliability evaluation using a security based model. IEEE Transactions on Power Systems, Vol. 13, No. 2, May 1998. Pp. 456-463.

[5] Rei, A.M., Leita da Silva A.M., Jardim, J.L., de Oliveira Mello, J.C. 2000. Static and Dynamic Aspects in Bulk Power System Reliability Evaluations. IEEE Transactions on Power Systems, Vol. 15, No. 1, February 2000. Pp. 189-195.

[6] Leite da Silva, A.M., Endrenyi, J. Wang, L. 1993. Integrated Treatment of Adequacy and Security in Bulk Power System Reliability Evaluations. IEEE Transactions on Applied Superconductivity, Vol. 3, No. 1, March 1993. Pp. 275-285.

[7] Huang, G., M., Yishan L. 2002. Power System reliability Indices to Measure Impacts Caused by Transient Stability Crises. 2002 IEEE Power Engineering Society Winter Meeting, January 2002. Pp. 766-771.

[8] Beshir, M., J. Farag, A., S., Cheng, T., C., 1999. New comprehensive reliability assessment framework for power systems. Energy Conversion and Management 40. Pp. 975-1007.

[9] Shahidehpour, A., M., Behera. A., K. 1989. Dynamics of Power System in Reliability Studies. Circuits and Systems, 1989. Proceedings of the 32nd Midwest Symposium on 14-16 Aug 1989. Pp. 268-272 vol. 1.

[10]Miki, T., Okitsu, D., Kushida, M., Ogino, T. 1999. Development of a Hybrid Type Assessment Method for Power System Dynamic Reliability. In: IEEE International Conference on Systems, Man and Cybernetics 1999. IEEE SMC '99 Conference Proceedings, Vol. 1. Pp. 968-973.

[11]Johannesson, T., Roos, R., Lindahl S. 2004. Reliability of protection systems – operational experience 1976-2002. In IEE the Eight International Conference on Developments in Power System Protection. Amsterdam, The Netherlands 5-8 April 2004. Pp. 303-306. ISBN 0 86341 385 4, ISSN 0537-9989, 827 p.

[12]Svensson, B.; Mathiasson, G.; Holst, S., Lindahl, S. 1992. Experience of Protection Equipment Maintenance - A Case Story, Report 34-105, CIGRE-Session, Paris, 30 August - 5 September, 1992, 9 pages.

[13]Pugh, J.S., Ferreira, L.R.C., Crossley, P.A., Allan, R.N., Goody, J., Downes, J., Burt, M. 1997. The reliability of protection and control systems for transmission feeders. In: IEE Conference Publications No. 434. Developments of Power System Protection (DPSP), Nottingham, April 1997. Pp. 10-13

[14]Ferreira, L.R.C., Pugh, J., Crossley, P.A., Allan, R.N., Goody J. 1996. Design and Reliability of Integrated Protection and Control Schemes. In: IEE Conference Publication No. 421. Power System and Control Management. Pp. 87-91

[15]Ferreira, L.R.C., Crossley, P., Allan, R.N., Downes, J. 2001. The Impact of Functional Integration on the Reliability of Substation Protection and Control Systems. IEEE Transactions on Power Delivery, Vol. 16, No. 1, January 2001. Pp. 83-88.

[16]Aabo, Y., Goin, R., Lundqvist, B. 2001. Risk analysis – a new aspect on protection and local control design. In: IEE Conference Publications 479, IEE Seventh International Conference on Developments in Power System Protection (DPSP) Amsterdam April 2001, Pp. 347-350.

[17]Pottonen L. A method for the probabilistic security analysis of transmission grids. A doctoral dissertation, Helsinki University of Technology 2005. Pp. 119+88. ISBN 951-22-7591-0, 951-22-7592-9 (pdf), http://lib.tkk.fi/Diss/2005/isbn9512275929/isbn9512275929.pdf

[18]IEEE/CIGRE 2004. Joint task force on stability terms and definitions. Kundur, P.; Paserba, J.; Ajjarapu, V.; Andersson, G.; Bose, A.; Canizares, C.; Hatziargyriou, N.; Hill, D.; Stankovic, A.; Taylor, C.; Van Cutsem, T.; Vittal, V. Definition and classification of power system stability. IEEE Transactions on Power Systems, Vol. 19, Issue: 3, Aug. 2004, pp. 1387 – 1401

[19]Rausand, M, Høyland, A. 2004. System Reliability Theory, Models, Statistical Methods, and Applications, Second Edition John Wiley & Sons, Inc. Hoboken, New Jersey, USA. ISBN 0-471-47133-X, 636 p.

[20]Borst, van der, M., Schoonakker, H. 2001. An overview of PSA importance measures. Reliability Engineering & System Safety. Elsevier Science Ltd. Vol. 72, 2001. p. 241-245.