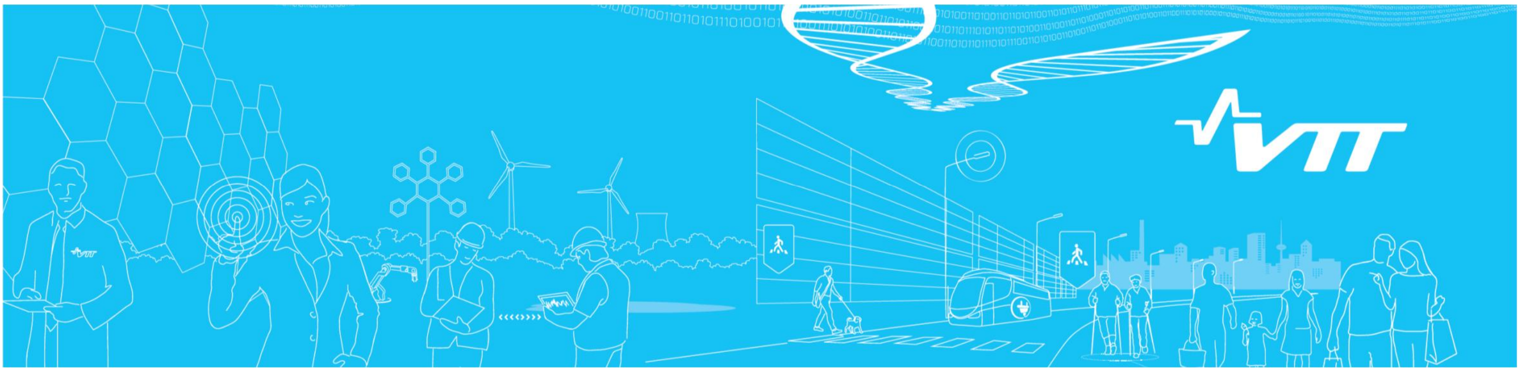
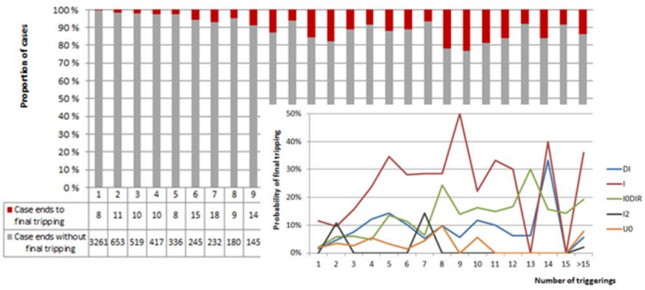


RESEARCH REPORT

VTT-R-05756-15



Fault and Disturbance Data Utilization in Distribution Network Operation

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Summary

The aim of this study was to seek answers to two main research questions:

1. Can disturbance and pre-trigger data be used to forecast network faults?
2. Can effectiveness of protection actions such as reclosing be estimated according to fault data?

These questions have clear implications in distribution network operation and planning principles. Assuming that network data stream could be monitored in order to estimate coming faults, network operation principles could be adjusted on affected area to reduce the number of disturbed customers.

In the study data collected from 52 substations of Elenia's distribution network during 1,5 years was analysed.

The result of data analysis was that in general level network faults cannot be predicted by number of triggerins or trippings. Anyway more detailed data analysis revealed some differences in probability of final tripping according tripping reason codes. To make reliable conclusions about this connection there is a need to repeat the analysis with larger data.

The other research question was related to effectiveness of fast and delayed reclosings. It can be concluded in general level that reclosings are effective in Elenia's distribution network preventing permanent fault in almost 90 % of reclosing events. The study also showed cases when effectiveness of reclosings is significantly lower.

Confidentiality	Confidential

Tampere 13.12.2015

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Preface

This report presents the results for the study on utilizing fault and disturbance data for fault prediction and network operation purposes. The study covers statistical analysis of measured data as well as studies on effectiveness of reclosing sequences.

The study has been performed as a direct project between VTT and Elenia. Hannu Koivuniemi, Heikki Paananen, Hanna-Mari Pekkala and Sirpa Repo from Elenia have contributed the study by collecting the data and providing deeper knowledge about the Elenia's distribution network.

Tampere 13.12.2015

Authors

Contents

1. Introduction

Modern distribution network automation systems provide high amounts of data for the operator. The data can come from protection relays, switching points, transformers, sensors and generally many other equipment monitoring systems.

Utilization of real time monitoring data in decision making can offer new possibilities for distribution network management in near future. Especially intelligent control systems making decisions independently seem very potential as they are able to reduce the workload of operation personnel. Distribution network management increasingly applies systems with artificial intelligence characteristics, especially FLIR (fault location, isolation and restoration) functionalities which could be expanded towards continuous monitoring of network data and independent operation.

A significant amount of data is already collected on pre-fault triggerings which do not lead to relay tripping and breaker operation. While these events do not exceed the actual tripping limit, it is anyhow relevant to assume that those are related to events which cause faults in the network. Such events can be observed due to tree touching overhead line or equipment, due to equipment condition or other technical problems. For instance, it could be possible to observe cable connection about to failure.

Use of pre-trigger data has not been widely applied so far and there are many open questions, especially on dependability of observations based on this data.

2. Objectives

The main research question in this study was to consider whether data available through network automation systems can be used to forecast network faults. This would enable precautionary actions such as adjusting network topology to minimize number of affected customers. Such precautionary actions would require some time to be taken, thus the timeframe considered has been starting from 2 minutes.

A further research question was to study the statistical effectiveness of reclosings. In case reclosings turn out ineffective on certain network area and/or certain fault types, they could be deactivated in order to reduce customer disturbances.

A longer perspective objective was to consider how the measurements and relating fault probabilities could be presented as a part of operations. For instance the idea of applying traffic light thinking on individual feeder level has been proposed. However findings of this study did not provide enough relevant information for this approach and thus this issue is not discussed further in this study. Figure 1 presents an example concept where two feeders have different profiles and the traffic light colours are defined accordingly.

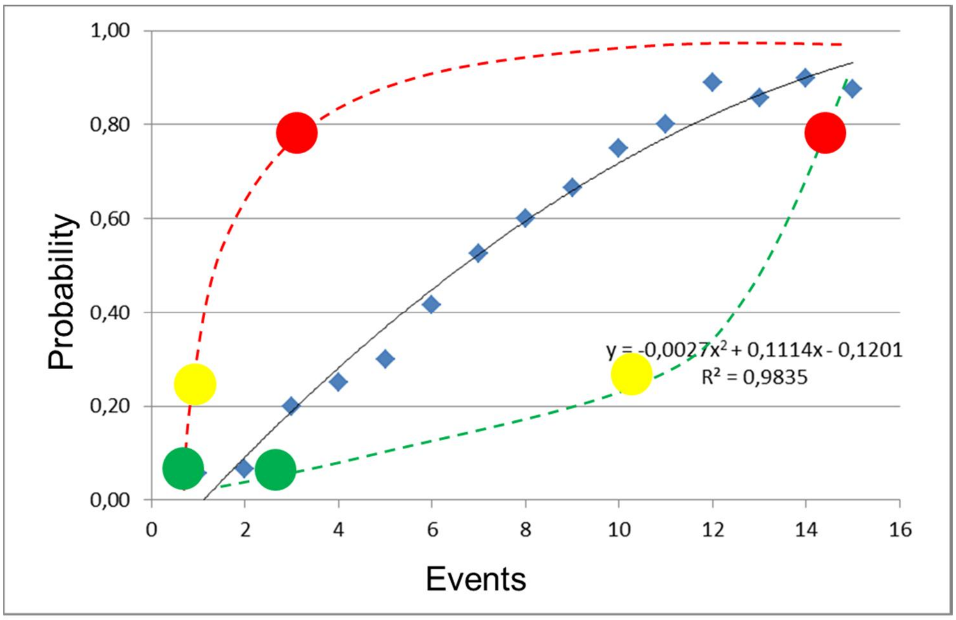


Figure 1. Example of two feeder fault probability profiles. Here the red dotted line indicates a more event critical feeder whereas green dotted line is a more stable feeder. The limits for traffic lights can be located on profiles and updated in real time.

Summing these main research questions, a higher-level objective was to consider how data available from automation systems can be processed statistically and applied for network monitoring purposes.

3. Description

The study was performed by means of analysing real network data provided by Elenia. The received data included recorded network events during time period 1.1.2014-11.7.2015 and covered 54 substations. The data was processed in different ways as described later in order to find the essential information. Certain storm periods were also removed from the material as they would otherwise strongly bias the data set.

4. Methods

4.1 Data pre-treatment

The delivered data included 693 749 rows in total. 657 439 rows were from substations and 36 310 rows from remote breakers. These rows included all data provided by network automation system (SCADA) which all were not relevant for this study. Thus before data analysis irrelevant rows were removed from the data.

First of all it was considered that during storms lot of events are recorded but for fault prediction purposes these events are irrelevant and they would affect the data bias significantly. Data during major storms, concerning all substations in the data, were removed. The storm days were: 19.-20.5.2014, 31.7.-1.8.2014, 2.-18.1.2015, 8.-9.4.2015 and 23.-24.5.2015.

Secondly the data included data rows recorded during scheduled inspections which also were considered irrelevant from the scope of this study. During inspections there are lot of events in the data relating only to inspection procedure. Inspections were not directly indicated in the data thus the following logic was used to recognize start and end times of scheduled inspection in a feeder:

- Start time: Variable ‘Arvo’=’AUKI’ and Variable ‘Status’=’OK’ and variable ‘Tunniste’ includes value ‘Q0’
- End time: Variable ‘Arvo’=’KIINNI’ and Variable ‘Status’=’OK’ and variable ‘Tunniste’ includes value ‘Q0’

While one of the feeders was under inspection, all data rows from all feeders in the same substation were removed. This was done as the event data from other feeders cannot be considered reliable during inspections.

Thirdly the data included lot of different kind of data irrelevant for this study. In addition to data rows recorded during storms and scheduled inspection it was removed all rows in which variable ‘Paikka’ begins with any other letter than ‘J’. Letter J marks 20 kV line feeders while other letters refer to higher voltage terminals or substation-level terminals. Additionally, all rows including one of the following text strings in variable ‘Tunniste’ were removed from analysed data:

- syöttö/syotto
- mittaus
- kond (refers to all words including string ‘kond’ e.g. kondensaattori)
- omak (refers to all words including string ‘omak’ e.g. omakäyttö)
- kela
- pätöteho / patoteho
- kisko (refers to all words including string ‘kisko’ e.g. kiskokäyttö)
- jännite / janite

In the Table 1 are shown reasons and numbers of removed rows. Some of the rows were categorised to more than one group of removed rows, thus the sum of rows during storms or inspections and other irrelevant rows is more than total number of irrelevant rows. From the whole data about 25 % of the rows were relevant for this study. Later it is described more detail how this data (159 815 rows) was treated for analysis of triggering and tripping and analysis of reclosings.

Table 1. Content of delivered data

	Number of rows
Number of rows in total	693 750
Rows recorded during storms	85 575
Rows recorded during scheduled inspections	171 574
Other irrelevant rows	411 481
Rows removed in total	533 935
Rows left in analysis	159 815

4.2 Data treatment for triggering and tripping analysis

The data contained records from 54 substations. Records from 40 substations have clear indication of final tripping i.e. text string 'Lopullinen laukaisu' in variable 'Tunniste'. For 14 substations without direct indication of final tripping following logic was used to recognize final trippings:

if (Variable 'Arvo'='AUKI') AND
(variable 'Tunniste' includes value 'Q0') AND
(during next 90 seconds there is no row where Variable 'Arvo'='KIINNI' and variable 'Tunniste' includes value 'Q0').

After final trippings were recognized and marked to data it was removed all rows which did not contained information about triggering (havahtuminen), tripping (laukaisu) or final tripping (lopullinen laukaisu). In other words the used in this analysis contained only rows where variable 'Tunniste' contained character '<'/'<<' or '>'/'>>' or the row indicated final tripping. Size of data was in this phase 92 781 rows.

After a final tripping there are typically recovery and testing actions which are irrelevant from this study point of view. Thus it was decided to remove rows recorded two hours after a final tripping. Final size of data in triggering and tripping analysis was 79 716 rows which is about 11 % of delivered data. Content of final data is presented in the Table 2.

Table 2. Content of polished data used in triggering and tripping analysis

Row type	Number of rows from substations	Number of rows from remote breakers	Number of rows in total
Triggering	62 584 (83 %)	3524 (87 %)	66 108 (83 %)
Tripping	12 490 (17 %)	352 (9 %)	12 842 (16 %)
Final tripping	575 (1 %)	191 (5 %)	766 (1 %)
Total	75 649 (100 %)	4 067 (100 %)	79 716 (100 %)

4.2.1 Definition of cases

The main objective of the study was to find out whether number of triggerings and trippings can predict occurrence of final tripping e.g. permanent fault. This objective can be transformed to two questions: ‘How many times there is a final tripping after x number of triggerings and trippings?’ and ‘How many times there is no final tripping after x number of triggerings and trippings?’. Answers to these questions can be found when we can recognize from the data triggerings, trippings and final trippings belonging to same event which is called a case in this report.

Cases were defined so that one case always relates to one feeder and maximum length of a case is 24 hours. For case definition the data is sorted by substation, feeder and time order where the oldest timestamp is first. Case begins from the first row of a feeder and ends either to final tripping or reaching the maximum case length i.e. 24 hours. In the Table 3 is given an example how cases are defined.

Total number cases created from the data was 10 329.

Table 3. Example of case definition

	Substation	Feeder	Time	Type of event	Number of triggerings in the case	Number of trippings in the case
Case 1	ETK	J01	23.4.2014 13.24.30.102	Triggering		
	ETK	J01	23.4.2014 13.40.30.334	Triggering		
	ETK	J01	23.4.2014 13.52.12.862	Tripping		
	ETK	J01	23.4.2014 13.53.30.102	Final tripping	2	1
Case 2	ETK	J03	15.5.2014 09.47.26.720	Triggering		
	ETK	J03	15.5.2014 10.13.25.129	Triggering		
	ETK	J03	15.5.2014 12.17.35.451	Triggering	3	0
Case 3	ETK	J03	23.8.2014 19.32.12.325	Triggering		
	ETK	J03	23.8.2014 19.57.29.530	Triggering		
	ETK	J03	24.8.2014 03.28.33.962	Tripping	2	1
	…					

4.3 Data treatment for reclosing analysis

Basic data treatment before reclosing analysis is same than described in chapter 5.1. Before reclosing analysis it was removed all data rows recorded during two hours after a final tripping because of fault recovery actions which are irrelevant for reclosing analysis.

4.3.1 Definition of reclosing

Reclosings were not directly indicated in the data so values in variable ‘Arvo’ and ‘Kuvaus’ were used to recognize reclosing events and successful of those. From the data it was looked after rows in which variable ‘Arvo’=’AUKI’ and variable ‘Kuvaus’ contains text string ‘Q0’ (abbreviated by Q0-AUKI in the logic description below). Recognition was done by three steps

Step 1: Reclosing event starts from the first row containing Q0-AUKI.

Step 2: If in three seconds after the start there is a new row containing Q0-AUKI then fast reclosing was assumed failed otherwise fast reclosing was assumed succeeded.

Step 3: If in 90 seconds after start there is a second row containing Q0-AUKI then delayed reclosing was assumed failed and the outcome of the reclosing event is permanent fault otherwise delayed reclosing was assumed succeeded.

Reclosings were assumed to be in use if in 90 seconds after the first Q0-AUKI row was at least one Q0-KIINNI row. Time limit 90 second selected to ensure that reclosing actions including only delayed reclosing will be included in the analysis.

Tripping reason of reclosing was the reason of the previous tripping before start time in step 1 in the above logic. The reason was looked in rows recoded 15 minutes before start of reclosing event. If no tripping was found in that time then reason for reclosing was marked as missing.

4.4 Descriptive statistical methods

Data analysis has been mainly done by descriptive methods like frequencies, crosstabs and visualizations. Aim of these descriptive methods is in first place to have clear impression of content and quality of data. The other aim is to have preliminary understanding of relationships between variables in interest.

In this study descriptive methods revealed essential conclusions and answers for the research questions. Thus in the Result chapter is presented results of descriptive analysis.

4.5 Logistic regression analysis

Logistic regression analysis can be applied when aim is to define how selected variables explain value of a dichotomous variable, for instance whether something is occurring or not. Result of logistic regression is an equation by which probability of occurrence can be calculated when values of explanatory variables are known.

In this study the variable to be explained is occurrence of final tripping which can have two values, final tripping is occurring or not. Thus logistic regression is applicable method in this study. Unfortunately the data used did not include variables by which occurrence of final tripping could be predicted by reasonable certainty. Variables used in analysis were:

- Number of triggerings with reason code DI
- Number of triggerings with reason code I
- Number of triggerings with reason code I0

- Number of triggerings with reason code I0DIR
- Number of triggerings with reason code I0INT
- Number of triggerings with reason code I0T
- Number of triggerings with reason code I2
- Number of triggerings with reason code IDIR
- Number of triggerings with reason code U0
- Number of triggerings with reason code VI
- Number of trippings
- Cabling rate
- Number of triggering codes

Because equation which have at least reasonable power to predict occurrence of final tripping could not be defined in Results chapter is not presented more details about the models.

5. Results of triggerings and trippings analysis

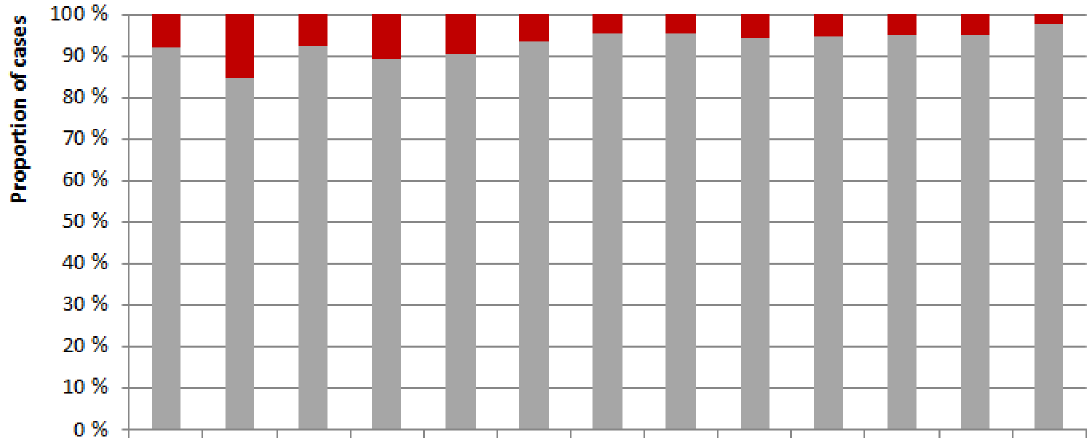
In this chapter is presented results of the analysis which aim was to find predictive model for final tripping. Results are presented by tables and graphics. The first two paragraphs presents generally duration and types of cases and rest of the paragraphs presents results of the analysis.

5.1 Duration of cases

Little over ten thousand cases were created from the data according the process described in section 4.2.1. Duration of most of the cases is less than two minutes. It should be noticed that duration of a case is 0 minutes if the case contains only one triggering or tripping. There were altogether 3255 cases containing only one triggering or tripping.

Table 4. Duration of cases.

Case duration	Frequency	Percent
0-2 min	6300	61 %
2-5 min	291	3 %
5-15 min	255	2 %
15-30 min	167	2 %
30-60 min	243	2 %
1-4 h	794	8 %
4-7 h	401	4 %
7-10 h	252	2 %
10-13 h	243	2 %
13-16 h	224	2 %
16-19 h	291	3 %
19-22 h	396	4 %
yli 22 h	472	5 %
Total	10 329	100 %



Duration of a case	0-2 min	2-5 min	5-15 min	15-30 min	30-60 min	1-4 h	4-7 h	7-10 h	10-13 h	13-16 h	16-19 h	19-22 h	yli 22 h
Case ends to final tripping	506	45	20	18	23	53	18	12	14	12	14	20	11
Case ends without final tripping	5794	246	235	149	220	741	383	240	229	212	277	376	461

Figure 2. In short cases probability of final tripping seems to be little higher than in longer cases.Total number of cases in figure in 10 329.

Cases which are shorter than two minutes are left out from the analysis because automated processes like FLIR cannot react fast enough for this timescale. Anyway cases with only one triggering or tripping are kept in analysis data because those cases provide information about predictability of final tripping after only one triggering. Thus number of cases in triggering and tripping analysis is 7479.

5.2 Description of case types

After all irrelevant data from the scope of this study is removed there are 7479 cases left in the data. Below in the Figure 3 is presented types of cases. The data includes in total 571 cases ending to final tripping but 152 of those are cases without any triggering or tripping. Almost all cases (about 90 %) which contain only a final tripping are recorded from remote breakers.

About 5 % of all cases which last longer than two minutes end to final tripping.

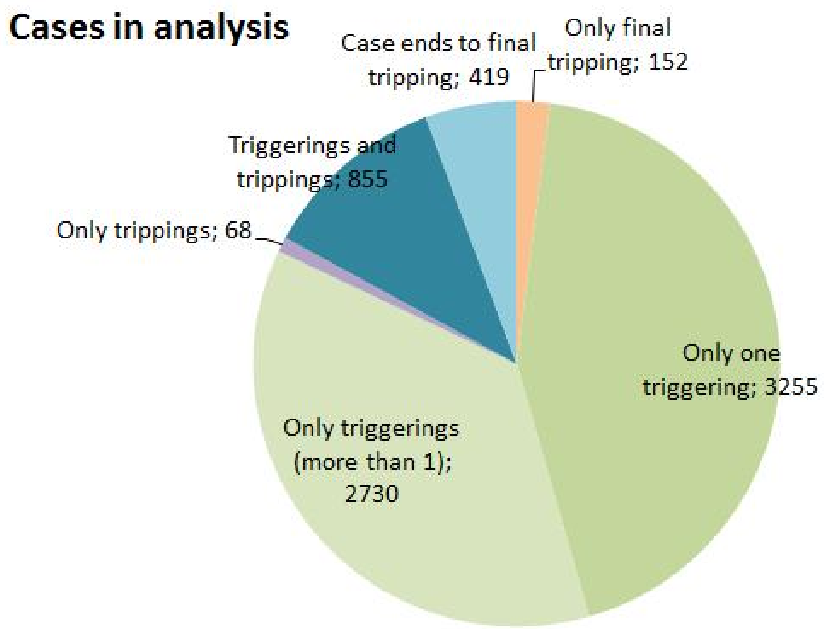
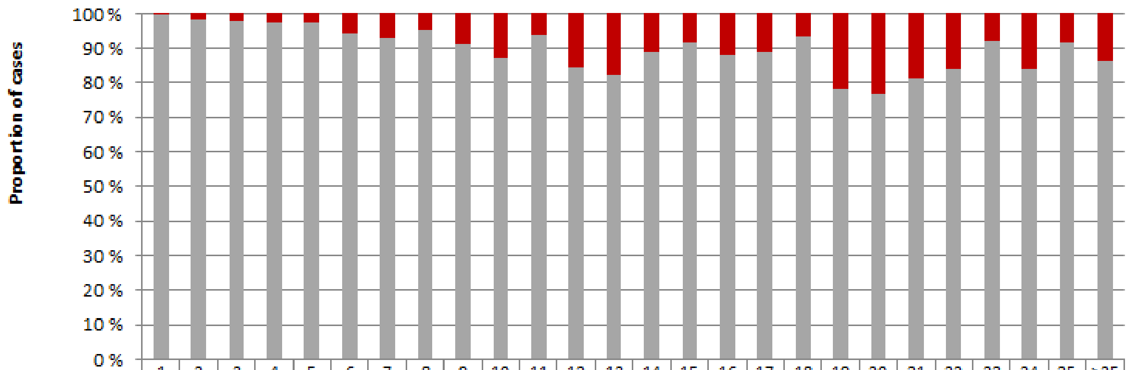


Figure 3. Cases type categorization in analysis data. The number after semicolon is frequency of cases belonging to the category. Total number of cases is 7479.

5.3 Relationship between number of events and final tripping

The main question of this study was can number of triggerings and trippings predict probability of final tripping. Based on data used in this study number of triggerings or trippings cannot in general predict occurrence of final tripping. From the Figure 4 it can be seen that in by any number of triggerings probability of a final tripping is not higher than about 20% although probability slightly increases when number of triggerings increases.

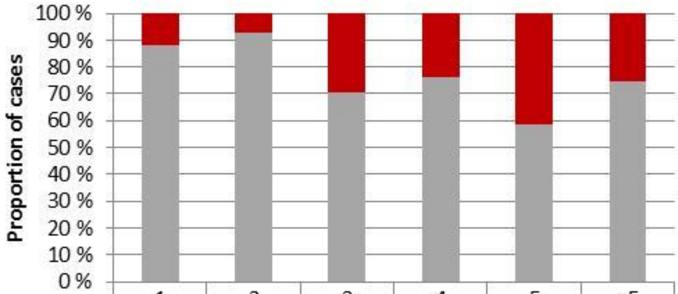


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	>25
Case ends to final tripping	8	11	10	10	8	15	18	9	14	16	6	17	13	8	5	7	5	3	8	6	5	3	2	4	2	41
Case ends without final tripping	3261	653	519	417	336	245	232	180	145	108	89	91	61	65	56	52	41	43	29	20	22	16	24	21	22	257

Number of triggerings in a case

Figure 4. Proportion of cases ending to final tripping does not substantially increase when number of triggerings increases.

Number of trippings predicts final tripping little bit better than number of triggerings. Number of trippings cannot considered as valuable indicator as number of triggerings because trippings cause disturbances to customers unlike triggerings.



	1	2	3	4	5	>5
Case ends to final tripping	52	21	55	27	34	62
Case ends without final tripping	378	263	132	86	48	184

Number of trippings in a case

Figure 5. Probability of a final tripping increases when number of trippings increases

Studying all cases without any categorizations it is clear that based on this data number of triggerings cannot be used to predict occurrence of final tripping. Anyway this kind of general overview can hide some information and number of triggerings might be relevant indicator in some categories despite general level results. In the next chapters are presented results of more detailed studies where predictability of final tripping is tried to improve by taking into account available background information, reason of triggering and a cabling rate of feeder.

5.3.1 Triggering code predicting final tripping

5.3.1.1 Number of triggering reason codes in a case

One case includes all triggerings and trippings recorded between case begining time and case ending time. Thus one case can include more than one triggering or tripping reason codes.

Firstly it was studied the relationship between number of triggering reason codes in a case and probability of a final tripping. In the previous chapter it was already stated that one triggering leads very rarely to final tripping. Cases with one triggering could have disturbed conclusions concerning this question because all these cases would have been categorized obviously to one reason code category. Thus in this analysis only cases with more than one triggering are in the data.

Table 5. Frequencies of cases according number of triggering reason code. Table includes only cases with at least two triggerings.

Number of reason codes in a case	Frequency	Percent
1	1895	47 %
2	1054	26 %
3	532	13 %
4	297	7 %
>4	210	5 %
Total	3990	

The relationship between number of triggering reason codes and probability of a final tripping is not strong but it should be noticed that if a case includes only one reason code the probability of a final tripping is very low, zero in practice (Figure 6). This conclusion holds even if number of trippings increases (Figure 7).

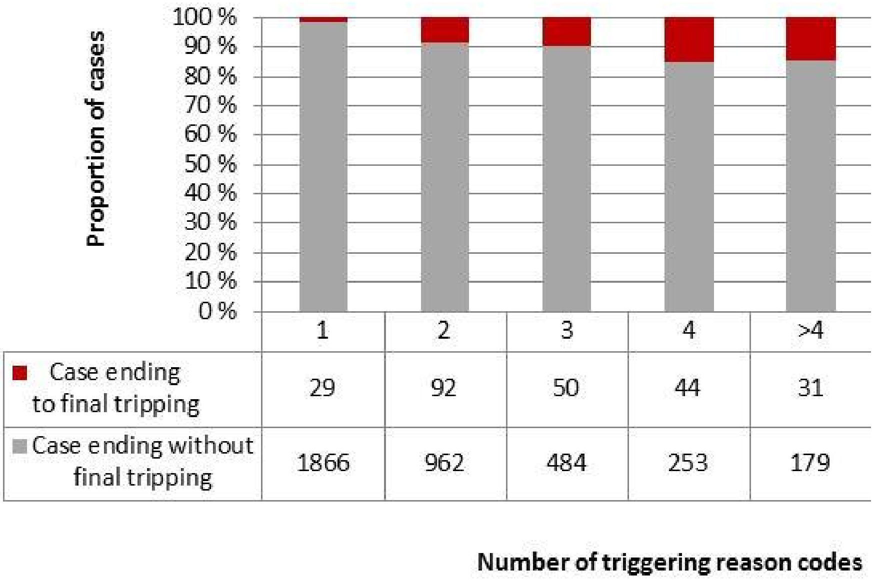
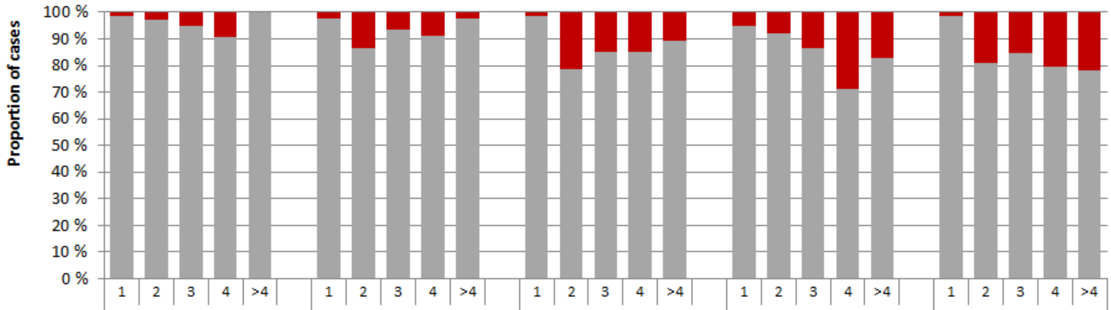


Figure 6. Probability of final tripping is practically zero if number of triggering reason codes is one. The figure includes all cases containing at least two triggerings.

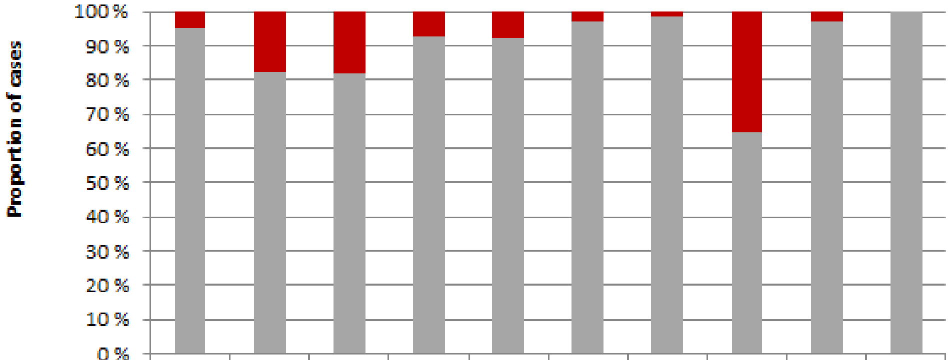


	2-5 triggering					6-10 triggering					11-15 triggering					16-20 triggering					>20 triggering				
	1	2	3	4	>4	1	2	3	4	>4	1	2	3	4	>4	1	2	3	4	>4	1	2	3	4	>4
Case ending to final tripping	15	15	7	2	0	7	42	12	10	1	2	21	12	9	5	3	3	6	10	7	2	11	13	13	18
Case ending without final tripping	1233	539	132	20	1	327	265	173	106	39	124	77	69	51	41	54	34	38	25	34	128	47	72	51	64

Figure 7. Probability of a final tripping is low if triggering code is same all the time despite number of triggerings. The figure includes all cases containing at least two triggerings.

5.3.1.2 Reason code of triggerings

The aim of this paragraph is to answer to question is there relationship between triggering reason codes and probability of a final tripping. In the Figure 8 is presented how existence of a certain triggering code in a case affects to probability of final tripping. There is some evidence that if one of the triggering codes in a case is ‘IDIR’ probability of a final tripping is about 30%, but the number of cases is too small for final conclusions.



	DI	I	I0	I0DIR	I0INT	I0T	I2	IDIR	U0	VI
Case ending to final tripping	141	183	26	187	42	1	6	33	88	0
Case ending without final tripping	2823	855	118	2439	510	35	386	61	3130	84

Figure 8. Probability of final tripping according triggering reason codes. One column/bar includes all cases containing current code despite how many other codes the case might include.

In addition to existence of a certain triggering code number of a certain triggering code is potential explanatory variable for probability of final tripping. This relationship is presented in Figure 9 and Figure 10 where is some evidence that several triggerings with code ‘I’ or ‘I0DIR’ are related to higher probability of final tripping. Unfortunately number of cases is too small to make reliable conclusions about this relationship.

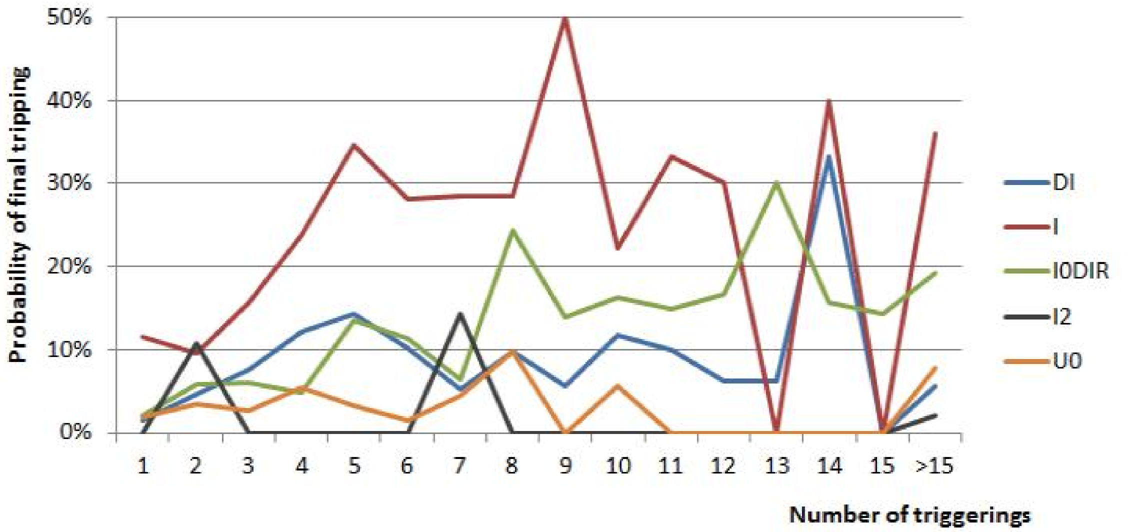


Figure 9. Probabilities of final tripping seems to vary according to reason for triggering.

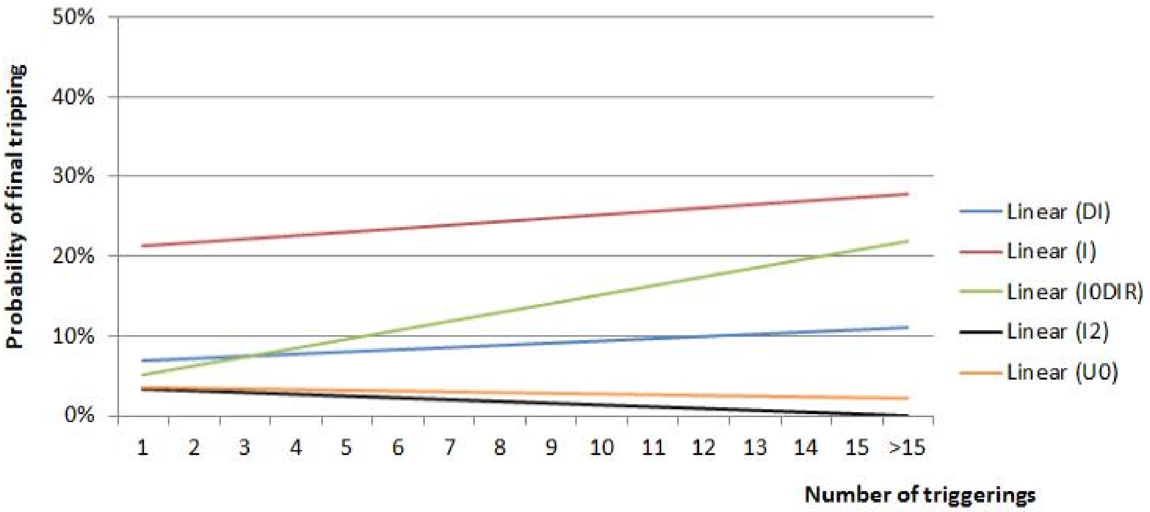
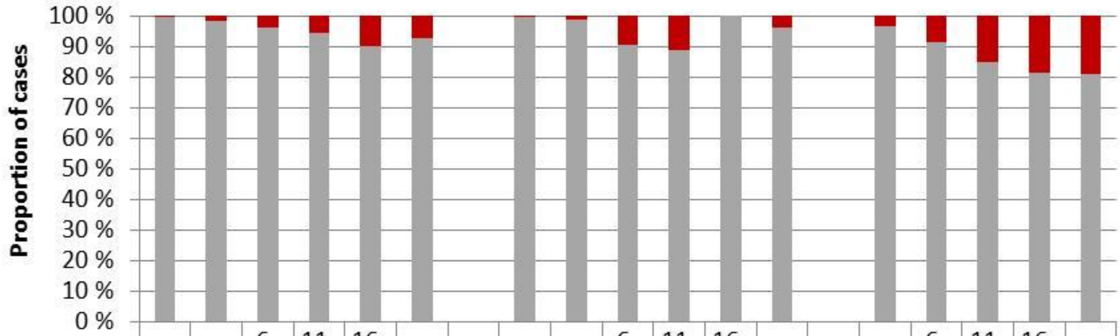


Figure 10. Trendlines showing how reason and number of triggerings reflects to probability of final tripping. Number of cases is too low for reliable conclusions about the trends.

Relationship between triggering codes and probability of final tripping was also studied by categorizing triggerings to earth faults and short circuits. If a case contains only earth faults or short circuits probability of a final tripping is always less than 10 % despite number of triggerings. If a case contains both earth faults and short circuits then probability increases according to number of triggerings but the even the highest probability is still less than 20 %. (Figure 11)



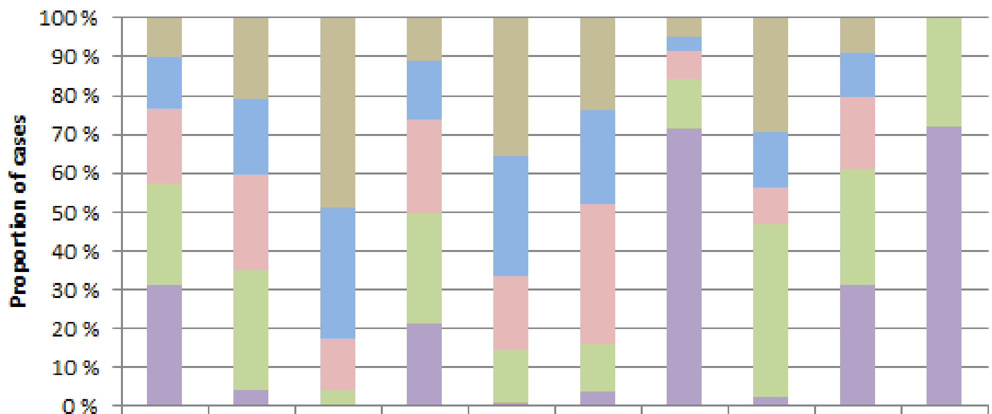
	Only earth faults						Only short circuits						Both				
	1	2-5	6-10	11-15	16-20	>20	1	2-5	6-10	11-15	16-20	>20	2-5	6-10	11-15	16-20	>20
Case ending to final tripping	4	16	12	5	3	6	4	7	21	12	0	3	16	39	32	26	48
Case ending without final tripping	205	892	302	86	28	78	121	584	199	94	42	80	449	409	182	115	204

Number of triggering reasons by Triggering types

Figure 11. Number of triggerings and triggering type explaining probability of final tripping.

It was also studied combination of different triggering codes. That study did not reveal any particularly interesting results from the scope of this project. In Figure 12 is shown how many triggering codes exist in a case if a certain code is involved. For example if ‘I2’ is typically the only code in a case and if a case includes code ‘I’ there is typically at least one other triggering code in the same case.

In the cases created were all together 97 different code combinations. Most of the combinations appeared only in few times so this data is too small to make conclusions about differences in probabilities of final tripping according different triggering code combinations. Table of all code combinations is in appendix 1.



	DI	I	IO	IODIR	IOINT	IOT	I2	IDIR	UO	VI
>4	196	209	70	209	174	6	13	27	182	0
4	257	192	48	289	152	6	10	13	221	0
3	386	245	19	457	94	9	19	9	364	0
2	509	304	6	547	67	3	34	41	586	11
1	616	42	0	401	4	1	192	2	609	28

Figure 12. One bar/column presents how many triggering codes a case includes when the code below a bar is in a case.

5.3.2 Cabling rate predicting final tripping

It was assumed that relationship between number of triggerings and probability of final tripping can vary according the type of feeder. Cabling rate was used as an indicator describing the feeder type. Cabling rate was categorized to four categories; 1) open line, 2) mainly open line and some underground cable, 3) mainly underground cable and some open line and 4) underground cable. Elenia's distribution network contains lot of open lines thus it is natural that major part (about 85 %) of feeders in this data belongs to first two categories where cabling rate is less than 50 % (Table 6). Almost all (94 %) final trippings are recorded from feeders which cabling rate is less than half.

Table 6. Number of feeders according cabling rate category

Cabling rate	Frequency	Percent
0-20 %	3623	51 %
20-50 %	2307	33 %
50-80 %	714	10 %
80-100 %	415	6 %
Total	7059	

According data available for this study there is no significant differences in probability of final tripping between cabling rate categories. From Figure 13 it can be seen that number of triggerings cannot consider reasonable indicator for final tripping in any cabling rate category.

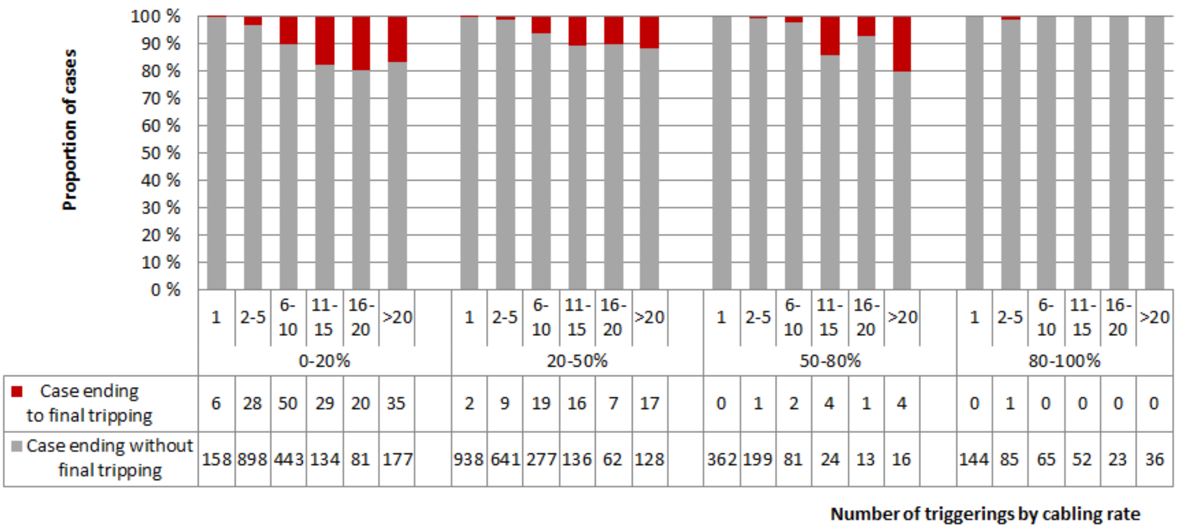


Figure 13. Predictability of a final tripping do not change according cabling rate

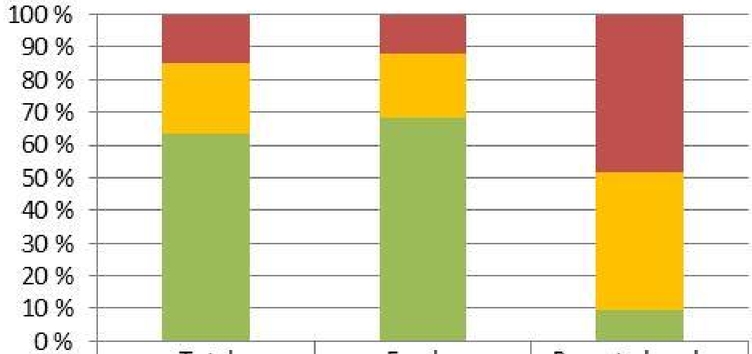
6. Results of reclosing analysis

Aim of reclosing analysis was to study are fast and delayed reclosings effective tool to prevent permanent faults in distribution network. To answer this question effectiveness of reclosings was studied in general, according to tripping reason, according to tripping threshold level and cabling rate of feeder.

The available data contained in total 3875 reclosing events. The logic used to find reclosings from the data is described in chapter 4.3.1.

6.1 Success of reclosings in general

On all reclosing events fast or delayed reclosing was able to handle about 85% of faults which is typical proportion according literature. The data contained reclosing events from remote breakers and feeders. If events from feeders and remote breakers are studied separately it can be noticed that reclosings are not useful in remote breakers. However, there were some uncertainties in data from some of the remote breakers which possibly impacts on this result. On feeders proportion of successful reclosing events is little less than 90 % (Figure 14).



	Total	Feeder	Remote breaker
Permanent fault	583	430	153
Successful delayed reclosing	837	705	132
Successful fast reclosing	2455	2425	30

Figure 14. Proportion of successful reclosings and permanent fault out of all reclosing events.

6.2 Reclosing analysis by tripping codes

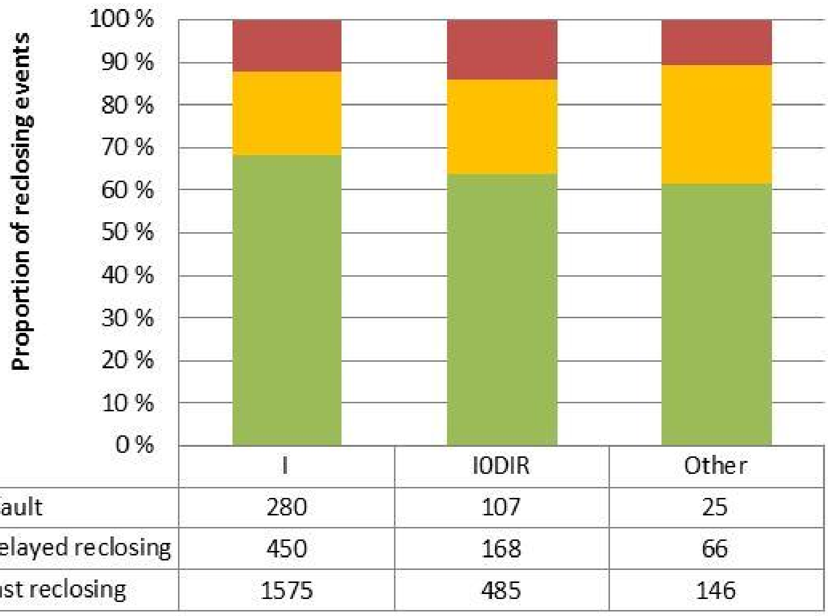
Last tripping code before beginning of reclosing event is typically either 'I' or 'I0DIR', proportion of other codes is only about 6 % (Table 7). Because of this in analysis is used three groups for tripping code; 'I', 'I0DIR' and other. Codes are also categorized to short circuits and earth faults.

The tripping code is missing for 15 % of all reclosing events. Half of events with missing code are from remote breakers and half from feeders. Only about 60 reclosing events recorded from remote breakers have a value for tripping code so events from remote breakers do not disturb this analysis and are not treated separately.

Table 7. Tripping codes leading to the reclosing sequence

Tripping code	Code type	Frequency	Proportion
I	Short circuit	2305	60 %
I0DIR	Earth fault	760	20 %
I0INT	Earth fault	118	3 %
IDIR	Earth fault	42	1 %
I0	Earth fault	41	1 %
U0	Earth fault	27	1 %
DI	Short circuit	8	0 %
I0T	Earth fault	1	0 %
Missing		573	15 %
Total		3875	

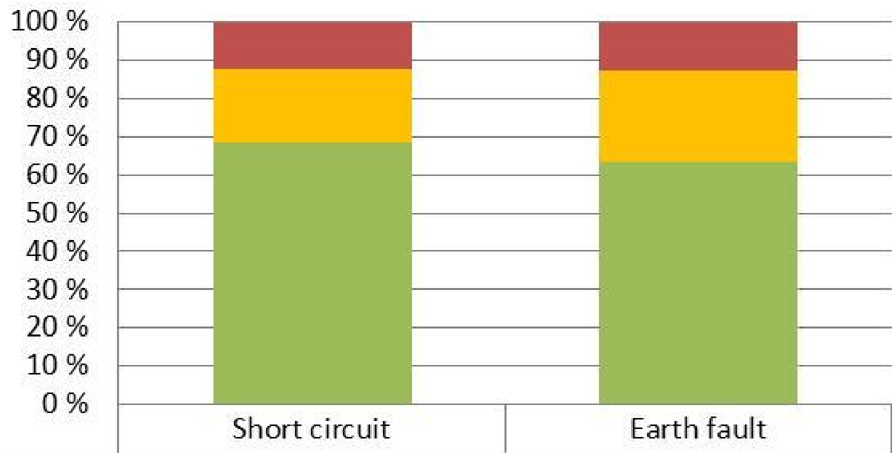
There are slight differences in effectiveness of reclosing according to the tripping code. When the tripping code is ‘I’ fast reclosing can prevent further consequences in 70 % of reclosing events and delayed reclosing prevent permanent fault in 20 % of events. When the tripping code is ‘I0DIR’ then fast reclosing can handle little over 60 % of reclosing events and delayed reclosing about 25 % of reclosing events.



	I	I0DIR	Other
Permanent fault	280	107	25
Successful delayed reclosing	450	168	66
Successful fast reclosing	1575	485	146

Figure 15. Successful of reclosings according tripping reason code.

Considering effectiveness of reclosings according earth faults and short circuits it should be noticed that short circuits are basically same than reason code ‘I’ and earth faults includes other reason codes except reason code ‘DI’. Thus results of short circuit and earth fault comparison are mainly same than presented above (Figure 16).



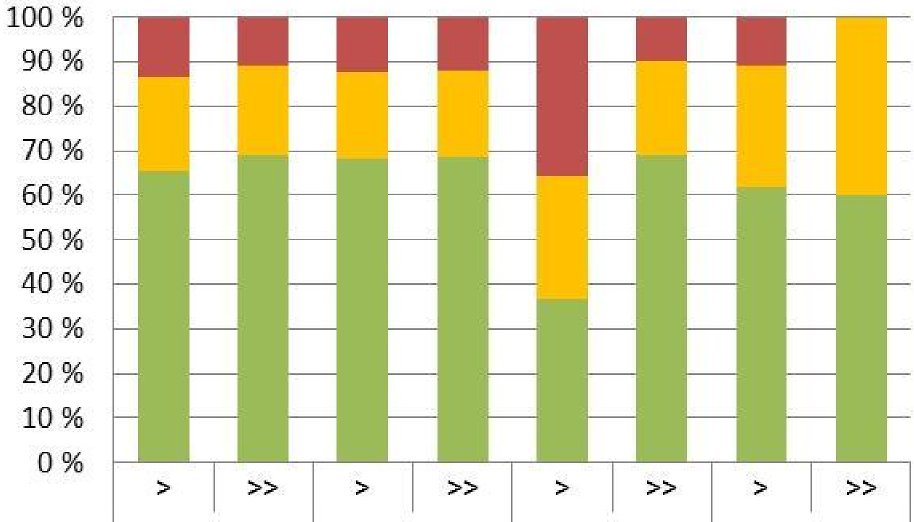
	Short circuit	Earth fault
Permanent fault	284	128
Successful delayed reclosing	451	233
Successful fast reclosing	1578	628

Figure 16. Successful of reclosings according reason type of tripping.

6.3 Reclosing analysis by tripping threshold level

Threshold level is defined from reason description (variable ‘Tunniste’) of the last tripping before reclosing event.

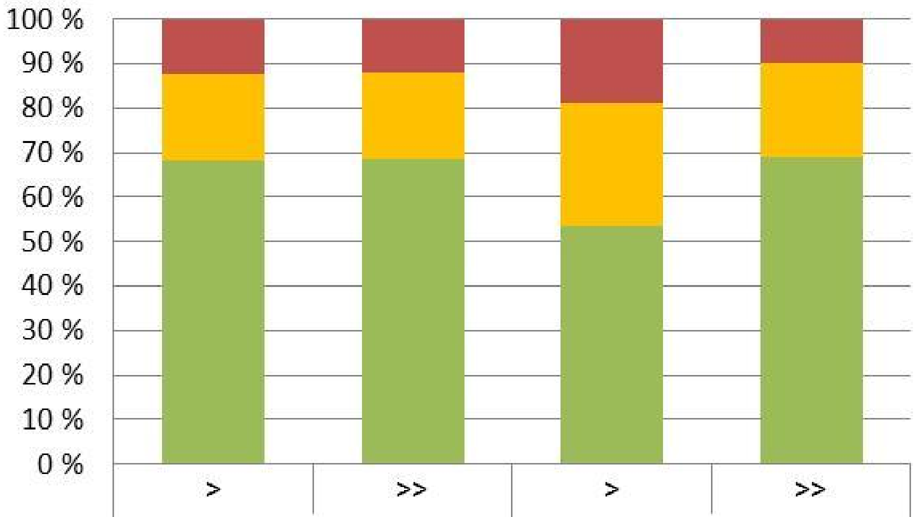
Effectiveness of reclosing in two different threshold levels is in general on same level as can be seen from the two leftmost columns in Figure 17. When threshold levels are studied further by tripping reason code is can be seen that if the tripping reason is ‘I0DIR’ and threshold level is ‘>’ then by fast reclosing can be prevented only about 25 % of further consequences. Unfortunately the number of reclosing events in this category is rather small so more data would be needed for reliable conclusions. Anyhow the results clearly indicate that reclosings for I0DIR slower threshold may be not beneficial.



	Total		I		I0DIR		Other	
	>	>>	>	>>	>	>>	>	>>
Permanent fault	265	147	196	84	44	63	25	0
Successful delayed reclosing	412	272	314	136	34	134	64	2
Successful fast reclosing	1283	923	1095	480	45	440	143	3

Figure 17. Successful of reclosings according tripping threshold level and reason of tripping

Categorizing tripping reason codes to short circuit and earth faults it can be seen that in earth fault with threshold '>' effectiveness of reclosings is worse than in other groups (Figure 18) but the difference is smaller than shown in Figure 17. So there is clearly a need for further investigation of reclosing effectiveness in different threshold levels.

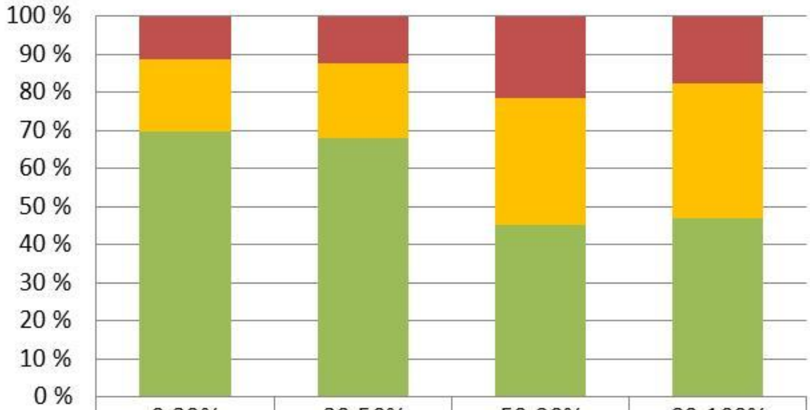


	Short circuit		Earth fault	
	>	>>	>	>>
Permanent fault	200	84	65	63
Successful delayed reclosing	315	136	97	136
Successful fast reclosing	1098	480	185	443

Figure 18. Successful of reclosings according tripping threshold level and type of tripping reason

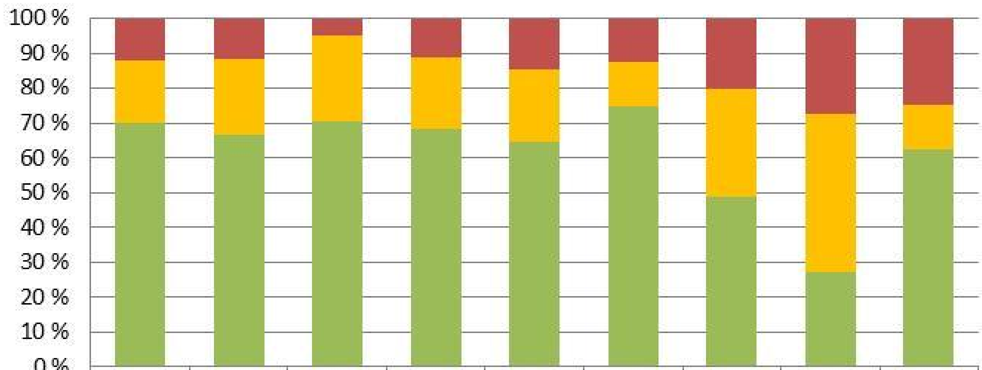
6.4 Relationship between cabling rate and effectiveness of reclosing

Based on data available in this study there is no evidence about significant differences between effectiveness of reclosings in different type of feeders (Figure 19). Tripping reason do not significantly affect successful of reclosings when cabling rate is taken into account (Figure 20). Again it should to be noticed that the data did not included many feeders which cabling rate is bigger than 50%. On the other hand this is not a big issue in this study because most interesting feeders are those with low cabling rates. Majority of reclosings occur on overhead lines and reclosings are not widely applied for cable feeders.



	0-20%	20-50%	50-80%	80-100%
Permanent fault	259	143	22	3
Successful delayed reclosing	429	224	34	6
Successful fast reclosing	1585	775	46	8

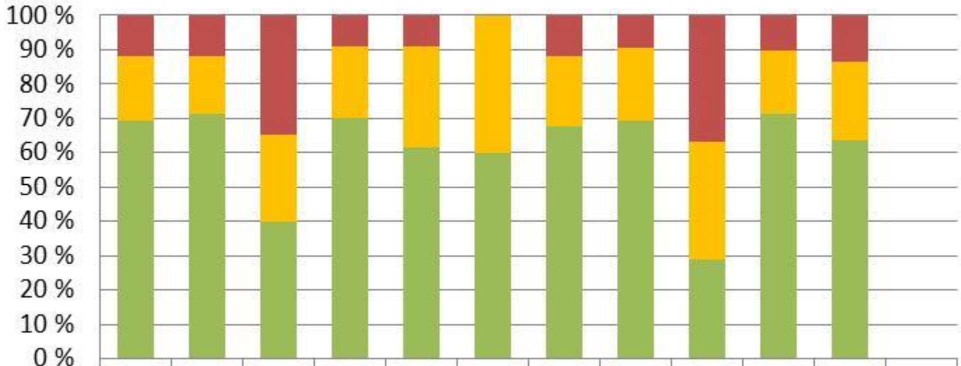
Figure 19. Successful of reclosings by cabling rate



	I	IODIR	Other	I	IODIR	Other	I	IODIR	Other
	0-20%			20-50%			50-80%		
Permanent fault	174	58	6	85	32	7	14	6	2
Successful delayed reclosing	260	105	30	156	45	7	22	10	1
Successful fast reclosing	1011	326	86	518	139	41	34	6	5

Figure 20. Successful of reclosings by triggering reason code and cabling rate.

It was also further studied whether effectiveness of reclosings varies if also threshold level is considered in addition to cabling rate and tripping reason. From Figure 21 can be seen that conclusions made previously about threshold level and tripping reason holds for both cabling rates which have enough data for this analysis. Reclosings are not beneficial in threshold level '>' with triggering code 'I0DIR' despite cabling rate of a feeder.



	Cabling rate 0-20%						Cabling rate 20-50%					
	I		I0DIR		Other		I		I0DIR		Other	
	>	>>	>	>>	>	>>	>	>>	>	>>	>	>>
Permanent fault	123	53	28	40	14	0	66	20	14	19	9	
Successful delayed reclosing	191	72	20	90	44	2	112	45	13	33	15	
Successful fast reclosing	703	309	32	303	93	3	373	145	11	130	42	

Figure 21. Effectiveness of reclosings by threshold level, triggering reason code and cabling rate

6.5 Effectiveness of reclosings on feeder level

It was assumed that effectiveness of reclosing can vary in different feeders. To study this assumption it is drawn to Figure 22 successful of reclosing in all feeders which have at least ten reclosing event. To Figure 23 is drawn all feeders which have at least 20 reclosing events, just to make figure more readable with less feeders in a same figure. From these figures it can be seen quite a big variation in proportion of reclosing events ending to permanent fault.

It was earlier (chapter 6.1) shown that reclosings related to remote breakers cannot prevent permanent failures. Because of this data from remote breakers were removed from this analysis.

Figure 22. Effectiveness of reclosings in feeders which have at least ten reclosing events in the data. Feeders are sorted by number of reclosing events. On the left side are feeders with most of events and on the right side feeders with ten events.

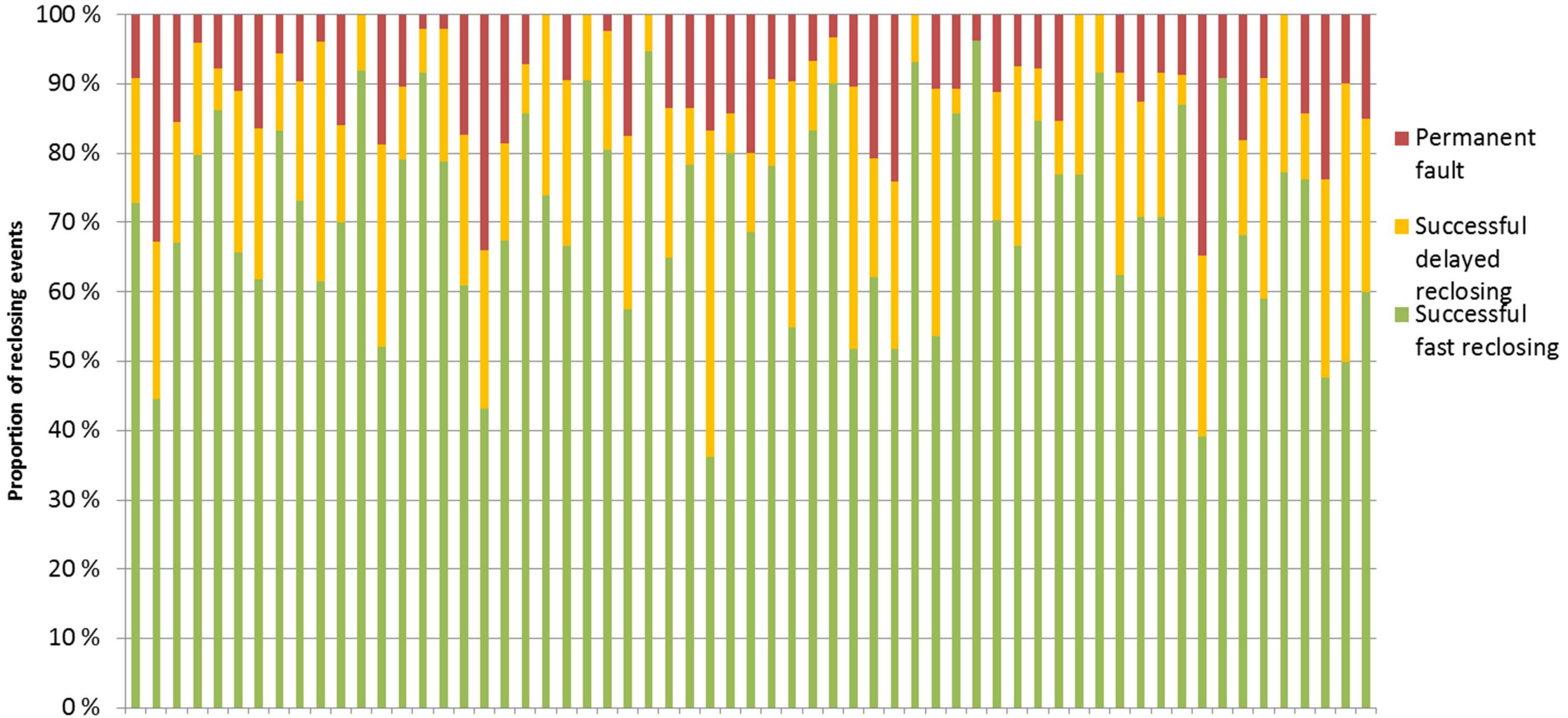


Figure 23. Effectiveness of reclosing in feeders which have more than 20 reclosing events in the data. Data from remote breakers are removed from the data. Feeders are sorted by number of reclosing events. On the left side are feeders with most of events and on the right side feeders with 20 events.

7. Validation of results

Validity of results from this study is highly dependent of the quality of available data. In general it can be said that data quality is in good level and amount of data is enough for results in general level but for detailed level analysis the data appeared to be too small. Below is further discussed the quality of data.

The available data included all records saved during 1,5 years from 52 substations in Elenia distribution network. Amount of substations is about a third of all substations. These substations were selected based on quality of available data which is reasonable argument for this study.

Third of substations is a good proportion of all stations and results are in basically generalized to whole network. On the other hand number of cases and especially amount of final trippings is rather small which leads to small number of cases in different categories and lack of reliable results when considering probability of final tripping in more detailed level.

Data recording practices set some challenges for this kind of study. The data included lot of data rows which were not relevant from this study of point of view and all the time it was not clear which rows are relevant and which not. For example the data did not include direct information about scheduled inspections or other manual actions. It was developed logics to recognize irrelevant rows from the data but some rows can be categorized wrongly because of difficulties to define comprehensive logics taking into account all different kind of recording practices.

There were differences in data collection practices between substations e.g. all substations did not have a record directly indicating a final tripping and description texts needed for categorizations have differences between substations.

Studying relationship between probability of final tripping and number of triggerings is based on definition of cases. A case is a series of recorded data rows belonging to same event. The collected data did not included direct indications which data rows compose a case. Logic created and described in chapter 4.2.1 is not perfect and there is possibility that one case includes rows from more than one case. If a case does not end to final tripping and a new case from the same feeder begins during 24 hours after the first case those will create only one case according used logic. This kind of wrongly categorized cases is a small proportion of the total cases and do not mislead results.

8. Conclusions

The main aim of this study was to find out can number of triggerings or trippings predict probability of final tripping. Based on data available in this study clear relationship between number of triggerings or trippings and probability of final tripping could not be found. In the level of whole data probability of final tripping increases slightly when number of triggerings increases but the probability of final tripping is even at highest level only about 20 %.

In detailed analysis when probability of final tripping was considered in different kind of feeders and according triggering reasons was found some interesting preliminary results but reliable conclusions would need repetition of this study with bigger data. For example number of triggering code ‘I’ seems to predict final tripping better that other triggering reasons but available data so small that so far this observation can be explained by chance.

In addition to descriptive analysis it was used logistic regression method to define a statistical model which could be used to estimate probability of final tripping. The result from this analysis was that with available variables it was not possible to predict occurrence of final tripping with reasonable certainty.

The closing analysis revealed that in general level fast and delayed reclosings work well and prevent permanent fault in almost 90 % of reclosing events in feeders. The detailed analysis showed slight differences in success of reclosing according tripping reason, if the tripping reason is ‘I’ the reclosings seems to work at best level. The most interesting result about reclosings is related to threshold level. The data provided rather strong evidence that when threshold level is ‘>’ in tripping code ‘I0INT’ the fast reclosing succeeded only in 25 % of reclosing events and fast and delayed reclosings together can prevent permanent fault only in 60 % of reclosing events.

Appendix 1.

Table of all triggering code combinations existing in cases

Combination of triggering codes in case	Case ending without final tripping	Case ending to final tripping	Total number of cases	Probability of a final tripping
U0	1968	2	1970	0 %
DI	1620	3	1623	0 %
I0DIR	1113	23	1136	2 %
I2	316		316	0 %
DI U0	275		275	0 %
I0DIR U0	248	5	253	2 %
DI I0DIR U0	184	10	194	5 %
I	128	26	154	17 %
DI I	102	34	136	25 %
DI I I0DIR I0INT U0	98	12	110	11 %
I I0DIR	84	22	106	21 %
DI I0DIR I0INT U0	92	7	99	7 %
DI I0DIR	88	3	91	3 %
DI I I0DIR	70	19	89	21 %
DI I I0DIR U0	66	15	81	19 %
VI	73		73	0 %
I0INT	65		65	0 %
I I0DIR U0	46	10	56	18 %
DI I U0	46	3	49	6 %
I0DIR I0INT	42		42	0 %
DI I I0DIR I0INT	31	9	40	23 %
I0DIR I0INT U0	38		38	0 %
I0DIR IDIR	21	17	38	45 %
I U0	24	7	31	23 %
DI I0DIR I0INT	25		25	0 %
I I0 I0DIR U0	21	2	23	9 %
DI I I0 I0DIR I0INT U0	19	3	22	14 %
DI I I0 I0DIR U0	16	6	22	27 %
I0INT U0	20		20	0 %
IDIR	6	12	18	67 %
I I2	17		17	0 %
DI I I0 I0DIR	10	5	15	33 %
I0DIR I2	15		15	0 %
I I0DIR I0INT	12	1	13	8 %
I I0DIR I2	11	2	13	15 %
I0T	12		12	0 %
DI I I0DIR I0INT IDIR	8	3	11	27 %
I VI	11		11	0 %
DI I0INT U0	10		10	0 %
DI I I0 I0DIR I0INT	8	1	9	11 %

DI I I0DIR IDIR U0	7		7	0 %
I I0 I0DIR	6	1	7	14 %
DI I I0DIR IDIR	6		6	0 %
DI I I0DIR I0INT IDIR U0	3	2	5	40 %
DI I IDIR	3	2	5	40 %
DI I0INT	5		5	0 %
I I0 I0DIR I0INT I2 U0	5		5	0 %
I I0DIR I0INT I2 U0	3	2	5	40 %
I I0DIR I2 IDIR	4	1	5	20 %
I0DIR I0T U0	5		5	0 %
DI I I0 I0DIR I0T	4		4	0 %
DI I I0 U0	3	1	4	25 %
DI I I0INT	4		4	0 %
DI I I0INT U0	4		4	0 %
I0 I0DIR U0	4		4	0 %
I0DIR I2 U0	4		4	0 %
DI I I0	3		3	0 %
DI I I0DIR I0T	3		3	0 %
I I0DIR I0INT I2	3		3	0 %
I0 U0	3		3	0 %
DI I I0 I0DIR I0INT IDIR U0	2		2	0 %
DI I I0DIR I0T U0	2		2	0 %
DI I I0T	2		2	0 %
DI I0 I0DIR	2		2	0 %
DI I0DIR I0T U0	2		2	0 %
DI IDIR		2	2	100 %
I I0		2	2	100 %
I I0 I0DIR I0INT	1	1	2	50 %
I I0 I0DIR I0INT I2	2		2	0 %
I I0 U0	1	1	2	50 %
I I0DIR I0INT U0	2		2	0 %
I I0DIR I2 U0	1	1	2	50 %
I0	2		2	0 %
I0T U0	2		2	0 %
I2 U0	2		2	0 %
DI I I0 I0DIR IDIR		1	1	100 %
DI I I0 I0INT U0	1		1	0 %
DI I0 I0DIR I0INT	1		1	0 %
DI I0 I0DIR U0	1		1	0 %
DI I0DIR I0T	1		1	0 %
DI I0DIR IDIR	1		1	0 %
DI I0DIR IDIR U0	1		1	0 %
DI I0T U0	1		1	0 %
I I0 I0DIR I0INT IDIR		1	1	100 %
I I0 I0DIR IDIR		1	1	100 %
I I0DIR I0T U0		1	1	100 %

I I0DIR IDIR		1	1	100 %
I I0INT I2	1		1	0 %
I IDIR	1		1	0 %
I0 I0DIR	1		1	0 %
I0 I0DIR I0INT	1		1	0 %
I0 I0DIR I0INT I2 U0	1		1	0 %
I0 I0DIR I0INT U0	1		1	0 %
I0DIR I0INT I2	1		1	0 %
I0DIR I0INT IDIR	1		1	0 %
I0DIR I0T	1		1	0 %
I0DIR IDIR U0	1		1	0 %