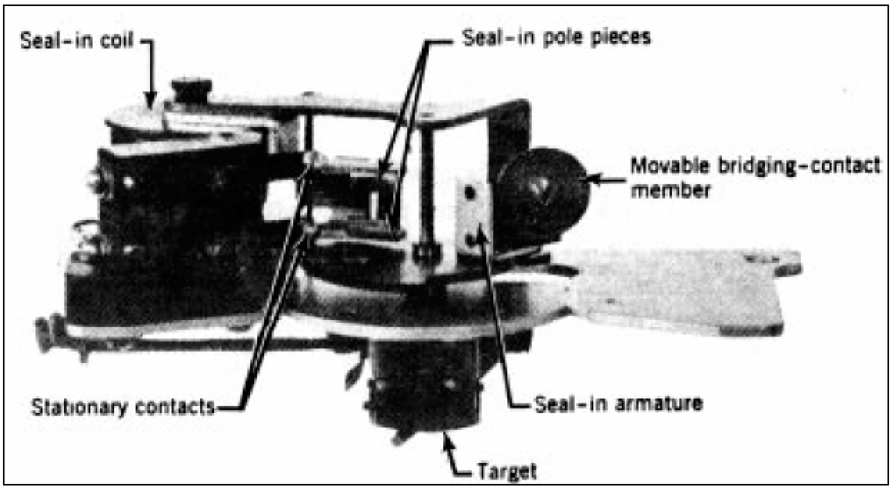
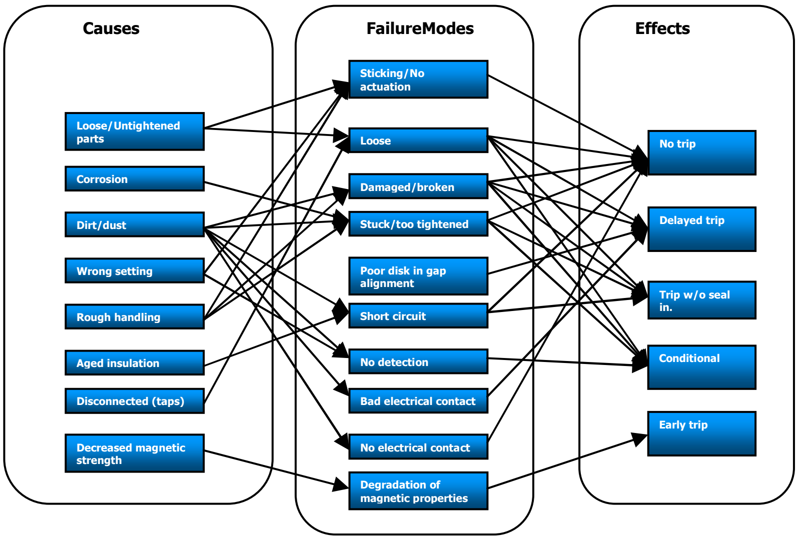
TU Delft

Evaluation of Failure behavior of Service Aged Electromagnetic Protective Relays

January 2006

M.J. Effendi





High Voltage Technology & Management

Evaluation of Failure behavior of Service Aged Electromagnetic Protective Relays

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Preface

In April 2005 I started my thesis research at the High Voltage Technology & Management group of the TUDelft about maintenance practices in the protective relaying field. The project has been initiated by Siemens Nederland N.V. but has been supervised by the TUDelft. During the 10 months of work on the thesis, Siemens Nederland N.V. supported me by bringing me into contact to specialists and engineers. In September Nuon Tecno joined the project. With the participation of Nuon Tecno it was possible to obtain more information about applied relaying practices.

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Introduction

Protective relays in medium voltage grids are used for protection of transformers, cables and loads. Protective relays are components used for recognising fault situations. In medium voltage grids the most common fault situations are:

- Overload
- Short circuit

In some situations it is necessary to disconnect a cable, transformer or a load. A circuit breaker disconnects these components as an act on the trip signal of a protective relay.

Medium voltage grids in the Netherlands are mainly protected by over current protective relays. Three kinds of protective relays of the over current type represent three generations of protection technology.

- First generation: Electromechanical kind
- Second generation: Static (analog) kind
- Third generation: Numerical (digital) kind

The first generation protective relays were commissioned in the late 40s and some of them are still in service and still form the majority in the protective relays. The maintenance approach on these protective relays hasn’t changed much for years. Though, recently the maintenance on protective relays has changed. This shift was caused by:

- Liberalization of Dutch energy market
- Changing insights in maintenance on protective relays
- Skill of maintenance engineers in the protection field
- No more support of manufacturers on these relays
- Availability of replacement parts

The changing insights in maintenance on protective relays form the outline of this thesis. System operators and also servicing companies are interested in whether the changes can be justified. In this thesis an effort was made to:

- Describe the current relaying practice in Dutch medium voltage grids
- Analyse the impact of outages caused by failing protective relays
- Analyze the maintenance process as it has been for years
- Analyze the maintenance process as it is applied now
- Review of the current maintenance process by comparison with the old process
- Formulate recommendations based on the review
- Describe a proposal for acquiring information from the maintenance process

By application of the Failure Mode Effect and Criticality Analysis (FMECA) technique it was possible to make this analysis. The FMECA IEC812 standard forms the basis of the new developed FMECA-sheet for protective relays.

1 Analysis of current protective relaying practices in Dutch medium voltage grids.

1.1. Current protective relaying practice in medium voltage grids.

To point out about which grids are included in this study, the following definition is adopted for medium voltage grids:

" c. Medium voltage networks: networks intended for transmission of electricity on a voltage
level of 1kV and above, but lower than 50kV."

Source: "Gebiedsindeling" augustus 2003 ,DTE , 1.1 Werkingssfeer en definities sub 1.1.2

Medium voltage networks in the Dutch grid are for a vast majority represented by 10 kV level installations. This study is mainly concentrated on 10 kV transportation/distribution networks commissioned by Dutch system operators. Private medium voltage installations are discarded from the scope of this study. The following picture describes some typical installation setups on the 10kV level:

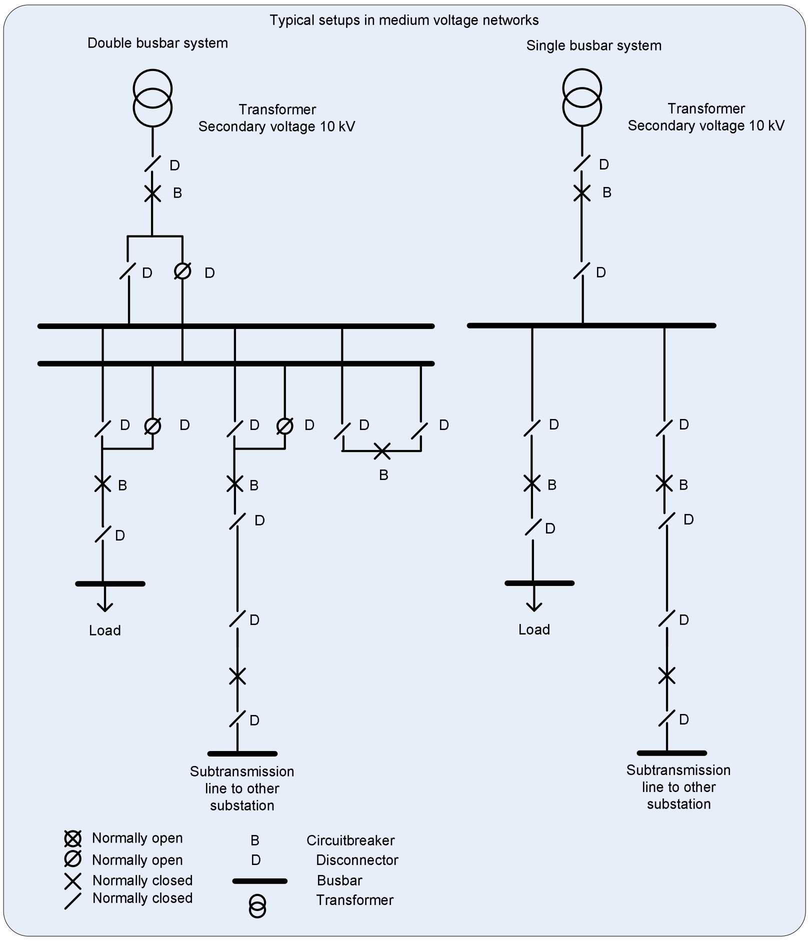

Figure 1. Typical Medium voltage substation setups

Protective relaying in these setups consists of several types of protection systems. The combination of a protective relay and a circuit breaker forms the protection system. Each of these systems takes their share in protecting a system component. For example such components are:

- Transformer
- Bus bar

- Feeder/line

These components need to be protected against the following fault situations:

- Over current or over voltage:
  Over currents occur during short circuit fault and over voltages occur after a lightning stroke.
- Duration (overload):
  In case of a line, cable or transformer carries a higher burden than the rated value.

In the Dutch medium voltage grids common types of protection are:

- over current protection,
- differential protection
- distance (zone) protection

In appendix 1 a short explanation of the operating principles of these protection types can be found.The following tables give an indication of the magnitude of the Dutch sub transmission/distribution grids and presence of protective relays in these grids.

Table 1. Magnitude of the Dutch medium voltage grid

Dutch medium voltage grid	
Voltage levels [kV] :	**3, 6, 10, 12.5, 20 and 25**
Number of substations:	**103177**
Grid length [km] :	**91930**

Table 1 is a summarized table of the information given in [1]. A more detailed look into [1] shows that medium voltage grids are mainly represented by 10 kV level installations. The next table shows gives an indication of the presence of protective relays in Dutch medium voltage grids.

Table 2 presence of microprocessor based protective relays

Type		Voltage ≤ 50 kV	
	Total	microprocessor based (numerical)	Percentage
Distance	3072	305	9.93%
Differential (zone)	2353	2	0.08%
Differential (transformer)	411	24	5.84%
Bus bar	35	0	0.00%
Over current	40132	981	2.44%
Total	46053	1362	2.96%

The information is shows what type of protection systems are used in medium voltage grids. Table 2 also shows that the majority of protective relays are of older kinds[1] of protective relays.

Remarks: 1) In the historical development of protective relays there have been three generations of protective relays. In the late 40s the first generation, the electromechanical type, came in to commission. In the early 70s the second generation, the electronic or analog type, was introduced as replacement for the first generation. The third generation, the numerical or microprocessor based type was introduced short after that. All three kinds of relays are still present in the medium voltage networks.

1.2. Reliability of protective relays

[5] Describes the reliability of the Dutch high/medium and low voltage grid. Most disturbances occur in medium voltage grids. Common causes for disturbances in the medium voltage grids are:

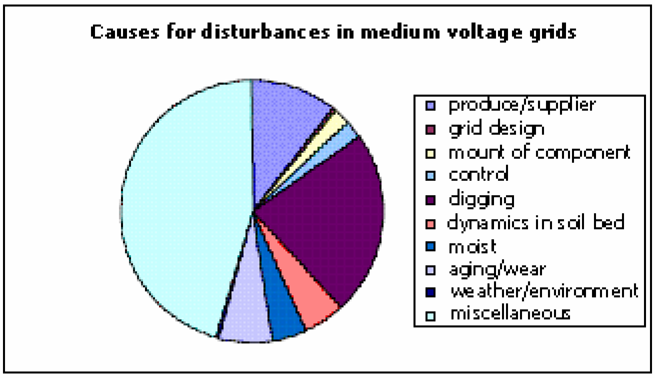

Figure 2 . Causes for disturbances in the medium voltage grid in 2002

Disturbances caused by failing protective relays are not mentioned.

Studies concerning the reliability of protective relays in the Dutch grids and especially the medium voltage grids are hardly available. Information about the performance of protection systems is only published in confidential company bound reports. [2] Presents results about the reliability of protective relays. The following table shows these results:

Table 3 total of protective relays that have failed the past 5 years

Total of protective relays that have failed in a time frame of 5 years					
	total	**Kind of failure of the protective relay**			
		Due to an outage	During inspection	During maintenance	Other
Electromechanical	43	8 (19%)	24 (56%)	11 (26%)	0 (0%)
Static (analog)	176	16 (9%)	44 (25%)	110 (63%)	6 (3%)
Numerical	37	6 (16%)	3 (5%)	12 (32%)	17 (46%)

The table shows that failures of electromechanical and static protective relays are mainly determined during the maintenance process.

A failure of numerical relay can also be determined by the so-called "live contact". This feature makes it possible to assess the operational status of a protective relay by means of distance monitoring. Numerical protective relays have built in self-check functions, which regularly test the functionality of the protective relay. The live contact signals in case of a fail of a self-check. This feature is not available in electromechanical and (most) types of static relays. For this reason regular checks are required.

1.3. Efforts in maintaining the reliability of protective relays

The maintenance process needed to keep the protective relays operative has been a labor-intensive process for years. This is typically valid electromechanical protective relays. Electromechanical relays were checked in intervals of once per year. These checkups consisted of inspecting visually, testing, recalibration and if needed repair and refurbishing to an as new component. Since protective relays are mainly idle components in their operational life, regular checks can only give confidence that a protective relay will operate when it is supposed to. The later introduced static and numerical protective relays didn't have the need for such intensive maintenance activities. Manufacturers have recommended only visually inspecting and testing these relays since no or hardly any serviceable parts are present in these relays. Also the intervals of checkups were changed into longer intervals. The next table shows the inspection intervals for all three generations:

Table 4. Inspection intervals of protective relays

Inspection intervals of protective relays					
	yearly	every 2 years	every 3 years	every 4 years	every 5 years
Electromagnetic	x	x	x		
Static			x		
Numerical				x	

1.4. Changes and trends in maintenance activities in protective relaying

The past 10 to 15 years new insights in maintenance activities on protective relays and the recent liberalization of the Dutch energy market have forced some changes in the maintenance of protective relays. These changes affected the maintenance activities on electromechanical relays especially. One major change was the approach in the regular checkups. Electromechanical relays consist of some delicate components like moving coils, springs, contacts etc. A checkup in which these components are subjected to some invasive actions could damage these parts. Invasive actions are for example the burnishing of contacts, adjusting springs and adjustment of other mechanical parts. To carry out a more invasive inspection, a criterion has been set. Only in the case of not passing a functional test because of faulty or drifted settings, a more invasive inspection is allowed. This approach resulted in a gradual loss of skill of maintenance personnel in maintaining electromechanical relays.

Another factor of influence is that the manufacturers stopped the technical support on electromechanical protective relays in the mid 80s. Since then power companies are depending on their stored supplies of replacement parts. A common practice is the replacement by a protective relay from a spare feeder.

The stretching of inspection intervals has become a common practice. The liberalization of the Dutch energy market is a factor of influence in this. The preventive maintenance approach is more and more shifting to a condition based approach.

2 Analysis on impact of (cascaded) outages caused by failing protective relays.

2.1. Technical consequences for a system operator.

System operators (TSOs/LNOs$^{1)}$)are supposed to reconnect the disconnected area as fast as possible. The general process of restoration after an interruption is described in [3], [4] and is described as follows:

1. Signaled interruption
2. Assign recovery crew
3. Localize fault
4. Isolate fault
5. Close opened switches en reroute grid openings

The time needed for signaling an interruption depends on the way this is done. Most substations are equipped with remote sensing and network control. In some cases this remote sensing fails to signal. In these cases the signaling time is determined by the first call of a customer. The following timeframes are greatly dependent on the company strategy for remedial actions. A recovery process can be divided in four different phases. These phases are:

1. Re-closing in outage opened switches
2. Re-closing original grid openings, in the case they were opened in the recovery process
3. Commissioning temporary power supply (only if this is a faster process than repair or interruption of maintenance)
4. Repair or interruption of maintenance.

The recovery process [8] in terms of time describes the time needed to restore the delivery of power. A total estimate time needed for restoration of power delivery can be described as follows:

$$\mathbf{T_{restoration} = T_{signaling} + T_{recoverycrew} + T_{localize} + T_{isolation} + T_{switching}} \qquad \textbf{(eq.1)}$$

Wherein $\mathbf{T_{switching}}$ depends on the way in which the power delivery is restored and can be defined by the described phases:

Phase 1: $\mathbf{T_{switching} = T_{reclose}}$ **(eq.2)**
Phase 2: $\mathbf{T_{switching} = T_{reclose} + T_{reroute}}$ **(eq.3)**
Phase 3: $\mathbf{T_{switching} = T_{alternative\ supply}}$ **(eq.4)**
Phase 4: $\mathbf{T_{switching} = minimum\ (T_{repair}\,,\ T_{maintenance\ interruption})}$ **(eq.5)**

The figure below shows a flow diagram wherein the decisions and the transitions in the restoration process are described:

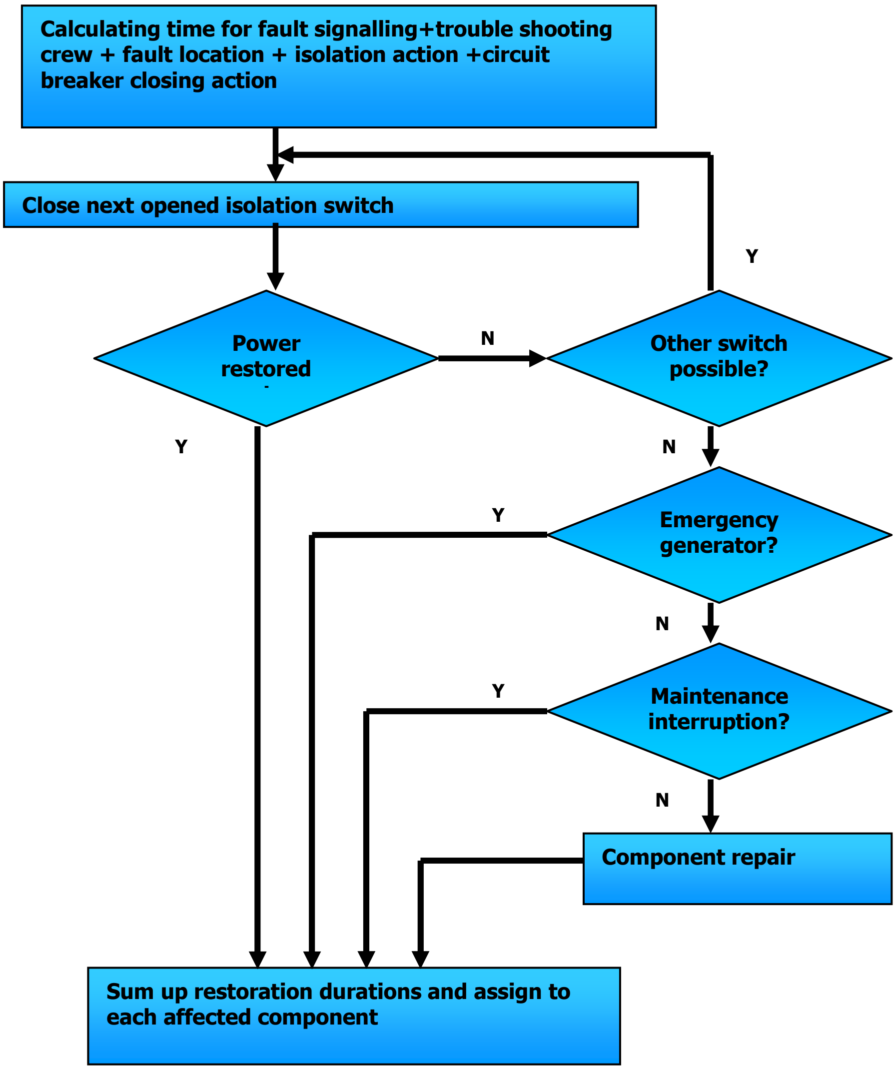

Figure 3. Restoration process flow diagram

The grid configuration determines the way in which recovery process is carried out greatly. Meshed or radial grid configurations have different technical recovery requirements. For a dead end feeder in a radial grid it may be necessary to arrange a temporary power supply. Medium voltage installations in meshed grids consist mostly of two or more bus bar (rail) systems. These setups shorten the duration of an outage considerably since a temporary supply doesn't have to be arranged in all cases. Without falling into detail, with a multi bus bar system it is possible to isolate the faulted bus bar and connect the feeder to another bus bar. Figure 1 in paragraph 1.1. shows some basic examples of these bus bar systems in medium voltage installations. The picture shows that a load behind a double bus bar setup can be supplied through either one of the two of the bus bars. The circuit breaker which is tripped by a defective relay can isolate the affected bus bar.

There are two choices in dealing with a defective protective relay:

- Repair
- Exchange

In practice, exchange of defective relays is carried out only. An exchange can be done by replacement of an equal type or new modern type relay. Replacing a defective relay by an equal type can be done in some cases. Sometimes such a relay is in stock, or a spare feeder is equipped with such a relay. Exchanging with relay from a spare feeder is a temporary solution and should be considered so. Exchanging a defective relay with a modern type takes more time since modern relays are not always interchangeable. Some technical modifications have to be made.

1) TSOs/LNOs : Transmission system operator / Local network operator

2.2. Economical impact of outage on system operators.

After an interruption is signaled, a transmission system operator (TSO)/local network operator (LNO) has to deal with the following issues:

- Restoration process
- Liability

The restoration process is strongly dependent on the setup of the infrastructure. A meshed or radial system requires in most cases different approaches. A more detailed explanation of the restoration process is given in the next paragraph. In some cases it is needed arrange a temporary power supply. The cost of such a measure is evaluated with what priority is given to the disconnected customers. A TSO/LNO can take the liability issue into account when deciding what measures should be taken in the restoration process. TSOs/LNOs are subjected to a directive enforced by DTE[1]. This directive states that customers are entitled to compensation when an interruption exceeds a 4-hour duration. In the frame below a more detailed description of this directive is given.

E 35	**for households and small businesses (shops, small offices) up to 60kW**
E 910	**for large businesses (offices, factories) in the range 60 kW-3 MW**
E 0,35/kW	**for large industrial customers of over 3 MW with a maximum of E 91.000)**

Excluded: in case of an outage due to actions of another service provider or if the outage is a necessary measure to reestablish balance in the system's supply and demand.

Source: "Advies van de Energieraad over aansprakelijkheid bij leveringsonderbrekingen", Algemene Energieraad, October 2003, p20.

According to [5, page 29], this directive is meant to stimulate TSOs/LNOs to prevent interruption duration to exceed 4 hours. In practice, this directive doesn't stimulate TSOs/LNOs to restore interruptions of short duration. In this sense, this directive influences the reliability/quality of the grid. To give an impression of the magnitude of paid compensation, in 2001 about 2,5 million euros was paid to a group of 60.000 customers.

The cost that comes with the process of restoration varies depending on what technical issues come into play. For this reason it can be useful to recognize certain scenarios. In these scenarios the influence of liability and the associated cost should be taken into account. Liability can become a more influencing factor since proposals for a new directive are being developed, see [6] for more background information.

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1) DTE Dutch office for energy regulation is an organization that enforces rules to prohibit the forming of monopolies and price agreements between network operators

2.3. Societal impact of outages.

It makes no difference for a customer what causes an outage. In the perspective of outages due to a failing protection system the impact of an outage will not be experienced differently than an outage caused by for example a damaged cable.

A report [7, pp iii-iv] describes the costs of outages and factors that influence the impact of an outage on society. These factors are:

- **The type of customer**
  Companies are confronted with three kinds of damages as a result of an outage. First they produce less and production has to be started up again. Second cost may rise. Sometimes extra labor input is needed. And third companies can still experience inconvenience after an outage because of stagnating supply input. The inconvenience of an outage for households is in most cases not being able to carry out housekeeping tasks or being entertained by television or radio.
- **Perceived reliability level**
  Dutch grids are, as stated in an earlier paragraph, very reliable. A consequence of this is that customers are relying on a continuous delivery of energy and will be less prepared for an outage.
- **The moment an outage is happening**
  An outage during working hours or in the evenings has for both types of customers different consequences. An outage during working hours is more inconvenient for companies than for households.
- **The duration of an outage**
  The duration of an outage can become a critical issue. In winter households or a company like a chicken farm cannot stay disconnected for a long period.
- **(Un) announced outage**
  Some outages are planned or are announced. In these cases the power company and the customers can take measures to minimize the effects of the outage.
- **Plenary / incidental outages**
  Also in these cases both customer and power company can take measures to minimize the effect of the outage.
- **Size of the supplied area**
  A larger supply area covers, in most cases, more customers. In these cases it is possible that loss of public services like trams, trains and metros are also consequences of an outage.

3 Technique for investigating failure behavior of e.m. protective relays

3.1. Investigating causes of failures of e.m. protective relays

The way in which protective relays fail can in some cases tell a lot about what cause is accountable for this. Experienced engineers recognize the failure modes and know what effects these failure modes have on the components performance. A systematic way for documenting this knowledge is the Failure mode effect analysis (FMEA). The international standard IEC 812 describes the FMEA procedure. As a supplemental analysis to the FMEA, a criticality analysis (CA) can be carried out to focus the attention scope on to critical failure modes. FMEA or FMECA is an exhaustive procedure that results in an as complete as possible list of failure modes and causes for failures. Also part of the FMECA is composing a list of failure detection methods. The herein presented results of the FMECA procedure [8] are supplemented with an analysis of current maintenance practices.

3.2. Failure mode effect and criticality analysis

FMECA is part of a maintenance development program called the Reliability Centered Maintenance (RCM) or Maintenance Steering Group (MSG) method. This program consists of 6 steps which result in the definition of a new maintenance program. The RCM/MSG[1] method is described as follows:

1. Technical system decomposition: *which components form the technical systems*
2. Recognize significant components: *on what components should attention be focused*
3. **Failure mode analysis:** *investigate failure behavior of components*
4. Select maintenance policy: *evaluate maintenance necessities*
5. Specify maintenance task: *describe process of maintenance activities*
6. Define maintenance program: *organize maintenance activities*

The goal of the FMECA procedure here is to find answers for the following questions:

- What is a likely way in which a part fails?
- What mechanisms are responsible for these failure modes?
- What could the effects be if the failures did occur?
- Is the failure in the safe or unsafe direction?
- How is a failure detected?
- What inherent provisions are provided in the design to compensate for the failure?

These questions are fitted into a structured approach defined by the IEC 812 standard. The IEC812 standard states that information necessary for carrying out a FMECA should cover (if possible) three categories. These categories are:

1. System structure
2. System initiation, operation, control and maintenance
3. System environment

The next figure shows an overview of how the FMECA is organized:

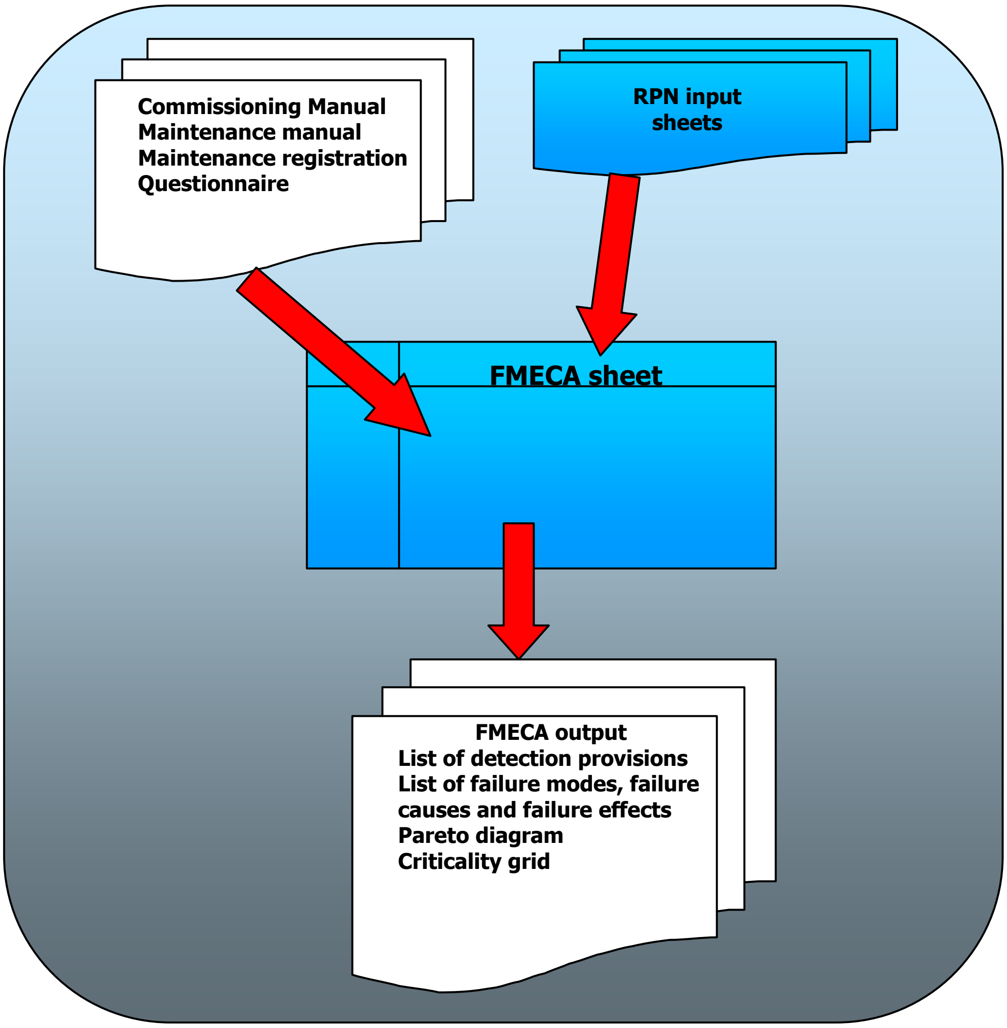


Figure 4. FMECA spreadsheet overview

This forms the basis for the developed FMECA spreadsheet program treated in the next paragraphs

Remarks

1) RCM/MSG- method as described by prof. K. Smit TUDelft, Aerospace engineering

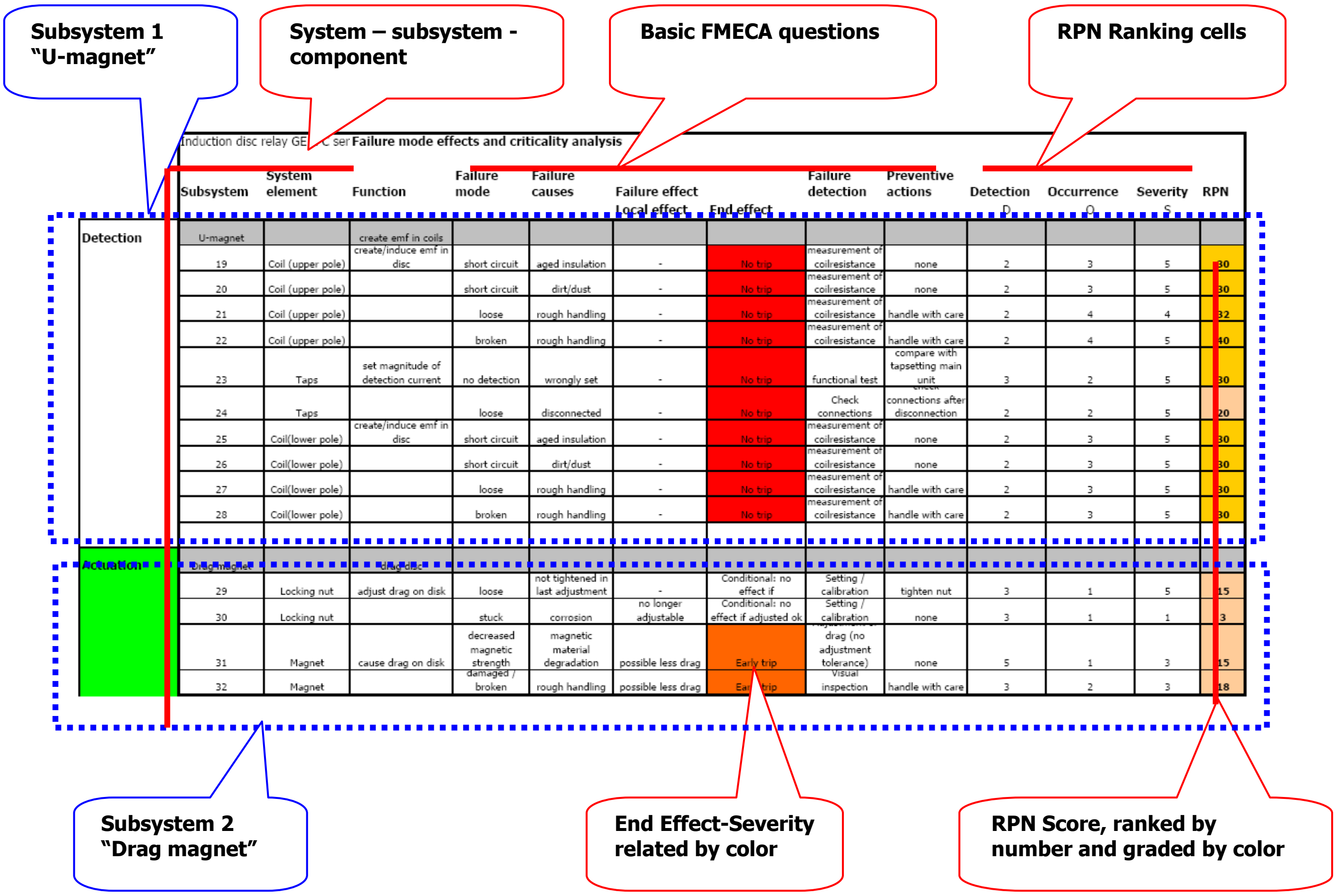
3.3. Implementation of the FMECA in a spreadsheet

The basic questions of a failure mode effect and critcality analysis can be implemented in a FMECA sheet. There are many appearances of this FMECA sheet, for this analysis one appearance is added to this collection. A regular FMECA sheet shows the a part of or the whole set of components that form the system. Here the whole set of components is subjected to the analysis. The here developed FMECA sheet is designed with help of the following design rules:

- A clear hierarchical view on system-subsystem-component relationships.
- Guidance in following the basic FMECA questions.
- Focus on RPN by seperate input sheets for RPN inputs (**Detection** and **Severity**)
- Focus on important end results (**End effect** and **RPN** ranking) by color sensitive Input/output.

3.3.1. Developed FMECA sheet

These design rules and evaluation of some appearances of FMECA sheets and the use of the IEC812 standard resulted in the following FMECA sheet:



Induction disc relay GE IAC ser **Failure mode effects and criticality analysis**

	Subsystem	**System element**	**Function**	**Failure mode**	**Failure causes**	**Failure effect Local effect**	**End effect**	**Failure detection**	**Preventive actions**	**Detection D**	**Occurrence O**	**Severity S**	**RPN**
Detection	U-magnet		create emf in coils										
	19	Coil (upper pole)	create/induce emf in disc	short circuit	aged insulation	-	No trip	measurement of coilresistance	none	2	3	5	30
	20	Coil (upper pole)		short circuit	dirt/dust	-	No trip	measurement of coilresistance	none	2	3	5	30
	21	Coil (upper pole)		loose	rough handling	-	No trip	measurement of coilresistance	handle with care	2	4	4	32
	22	Coil (upper pole)		broken	rough handling	-	No trip	measurement of coilresistance	handle with care	2	4	5	40
	23	Taps	set magnitude of detection current	no detection	wrongly set	-	No trip	functional test	compare with tapsetting main unit	3	2	5	30
	24	Taps		loose	disconnected	-	No trip	Check connections	connections after disconnection	2	2	5	20
	25	Coil(lower pole)	create/induce emf in disc	short circuit	aged insulation	-	No trip	measurement of coilresistance	none	2	3	5	30
	26	Coil(lower pole)		short circuit	dirt/dust	-	No trip	measurement of coilresistance	none	2	3	5	30
	27	Coil(lower pole)		loose	rough handling	-	No trip	measurement of coilresistance	handle with care	2	3	5	30
	28	Coil(lower pole)		broken	rough handling	-	No trip	measurement of coilresistance	handle with care	2	3	5	30
Actuation	Drag magnet		drag disc										
	29	Locking nut	adjust drag on disk	loose	not tightened in last adjustment	-	Conditional: no effect if	Setting / calibration	tighten nut	3	1	5	15
	30	Locking nut		stuck	corrosion	no longer adjustable	Conditional: no effect if adjusted ok	Setting / calibration	none	3	1	1	3
	31	Magnet	cause drag on disk	decreased magnetic strength	magnetic material degradation	possible less drag	Early trip	drag (no adjustment tolerance)	none	5	1	3	15
	32	Magnet		damaged / broken	rough handling	possible less drag	Early trip	Visual inspection	handle with care	3	2	3	18

Figure 5. Developed FMECA sheet

The call-out balloons show how the FMECA sheet is organised and the influence of three of the design rules.

3.3.2. Inputs of the FMECA sheet

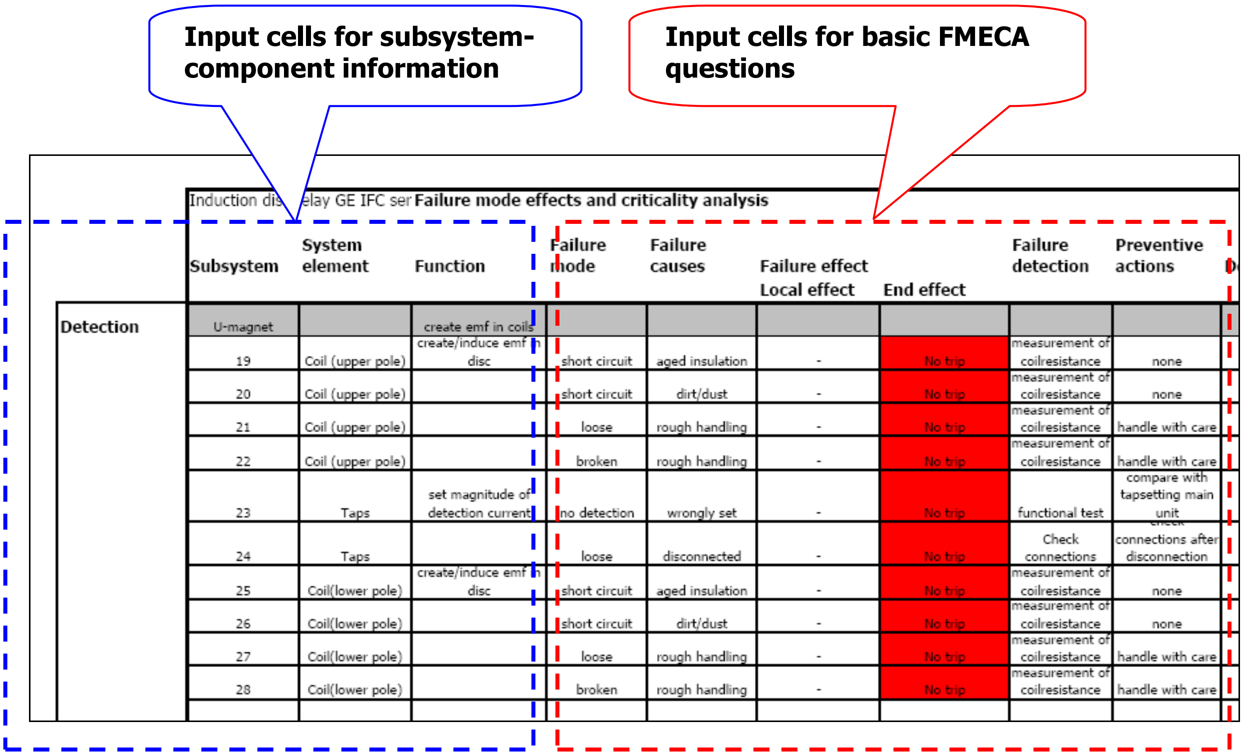
The basic input of a FMECA sheet is the textual description of the following:

- Subsystem.
- System element (component).
- Function.
- Failure mode.
- Failure cause
- Local effect of failure
- End effect of failure
- Detection provisions
- Preventive actions

Information about these subjects can be obtained from:

- Technical manuals
- Maintenance descriptions
- and other related documents

The described subjects cover most basic FMECA questions. The next picture shows how the basic input is organised:



Induction dis elay GE IFC ser **Failure mode effects and criticality analysis**

	Subsystem	System element	Function	Failure mode	Failure causes	Failure effect Local effect	End effect	Failure detection	Preventive actions
Detection	U-magnet		create emf in coils						
	19	Coil (upper pole)	create/induce emf in disc	short circuit	aged insulation	-	No trip	measurement of coilresistance	none
	20	Coil (upper pole)		short circuit	dirt/dust	-	No trip	measurement of coilresistance	none
	21	Coil (upper pole)		loose	rough handling	-	No trip	measurement of coilresistance	handle with care
	22	Coil (upper pole)		broken	rough handling	-	No trip	measurement of coilresistance	handle with care
	23	Taps	set magnitude of detection current	no detection	wrongly set	-	No trip	functional test	compare with tapsetting main unit
	24	Taps		loose	disconnected	-	No trip	Check connections	check connections after disconnection
	25	Coil(lower pole)	create/induce emf in disc	short circuit	aged insulation	-	No trip	measurement of coilresistance	none
	26	Coil(lower pole)		short circuit	dirt/dust	-	No trip	measurement of coilresistance	none
	27	Coil(lower pole)		loose	rough handling	-	No trip	measurement of coilresistance	handle with care
	28	Coil(lower pole)		broken	rough handling	-	No trip	measurement of coilresistance	handle with care

Figure 6. Input frame for subsystem-component information and basic FMECA questions.

One design rule concerns the separated input of the Risk Priority Number ranking (RPN). It's a ranking method for recognizing the most critical failures by giving them a score. This ranking method makes it possible to analyze the failure by use of PARETO analysis. The PARETO analysis arranges the results by the weight of the RPN ranking.

The PARETO analysis is explained further on. The RPN consists of the multiplication of 3 scores, namely:

$$RPN_c = D \times O \times S \qquad \textbf{(eq.5)}$$

RPN_c : Risk priority number of component
D : Detection score
O : Occurrence score
S : Severity score

In this FMECA sheet a 5 level score has been applied. This 5 level score is not described by a standard. Here the choice for 5 levels is based on how the information is obtained. In an interview questions are answered intuitively. A question could be constructed by for example:

Does component x fail? And in what extent does this occur? Recurrent/conceivable/sporadic/isolated or unlikely

In a qualitative approach it is possible to apply a score method as proposed here. The possible outcomes of the 5 level scores are:

Table 5. possible outcomes of a 5 level score

1	1	1	**1**
1	1	2	**2**
1	1	3	**3**
1	1	4	**4**
1	1	5	**5**
1	2	2	**4**
1	2	3	**6**
1	2	4	**8**
1	2	5	**10**
1	3	3	**9**
1	3	4	**12**
1	3	5	**15**
1	4	5	**20**
1	5	5	**25**
2	4	4	**32**
2	5	5	**50**
2	4	5	**40**
3	5	5	**75**
4	5	5	**100**
5	5	5	**125**

This uniform score method results in the following 5 level RPN:

Table 6. RPN score categories

RPN = 1
1 < RPN ≤ 25
25 < RPN ≤ 50
50 < RPN ≤ 100
100 < RPN ≤ 125

In the end result, the RPN, also 5 levels are used for the separation of levels. In the FMECA sheet these end result of the RPN calculation can be found in numerical way and by the corresponding color as indicated in the figure above.

The 5 level score is translated to the RPN categories in the following way:

Table 7. Score tables for RPN inputs

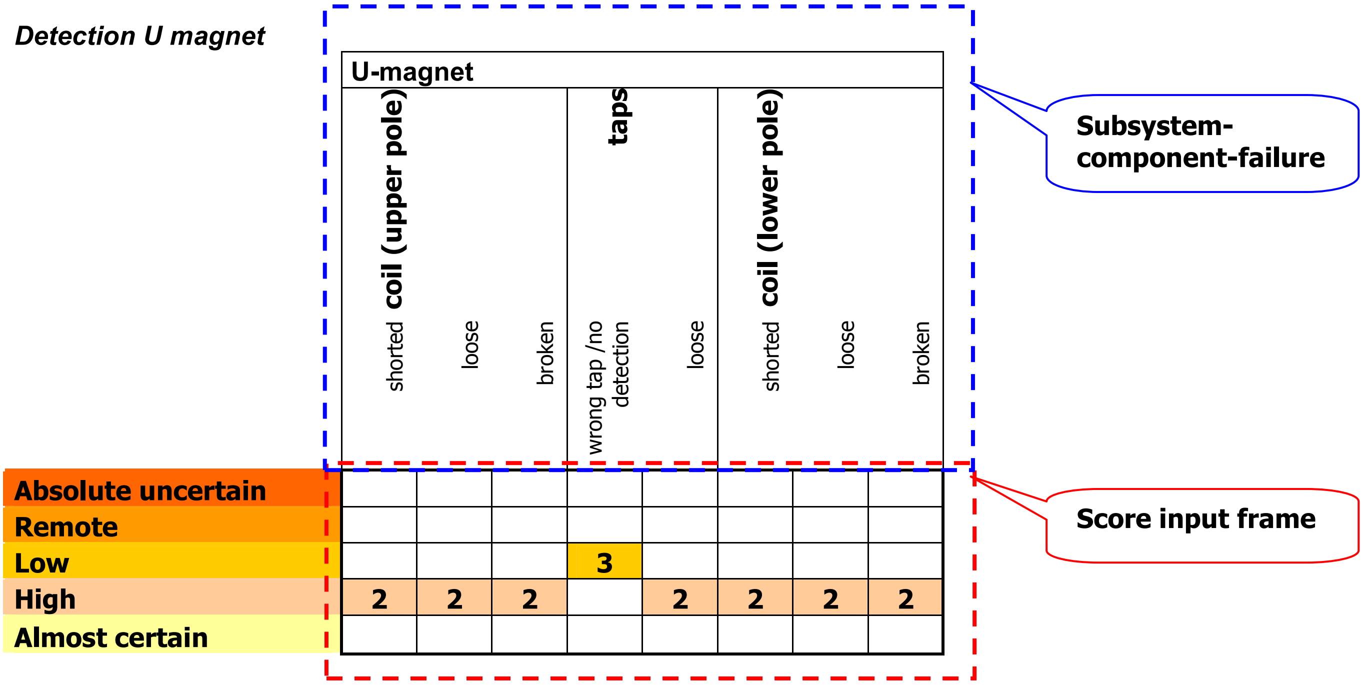
Severity score	
Score	
catastrophic	5
critical	4
moderate	3
marginal	2
minor	1

Detection score	
Score	
Absolute uncertain	5
Remote	4
Low	3
High	2
Almost certain	1

Occurrence score	
Score	
Recurrent	5
Conceivable	4
Sporadic	3
Isolated	2
Unlikely	1

- The severity score is related on the end effect of a failure mode.
- The detection score is based on the likelihood of detecting a failure with the means and skill of maintenance personnel.
- The occurrence score is based on information from interviews.

The score tables show a color coding. This color coding is active in the separate input frames that make an input sheet. It's a visual aid that makes the input sheet more readable and ensures that all inputs are filled out. The following picture shows an example of a part of a Detection input sheet:

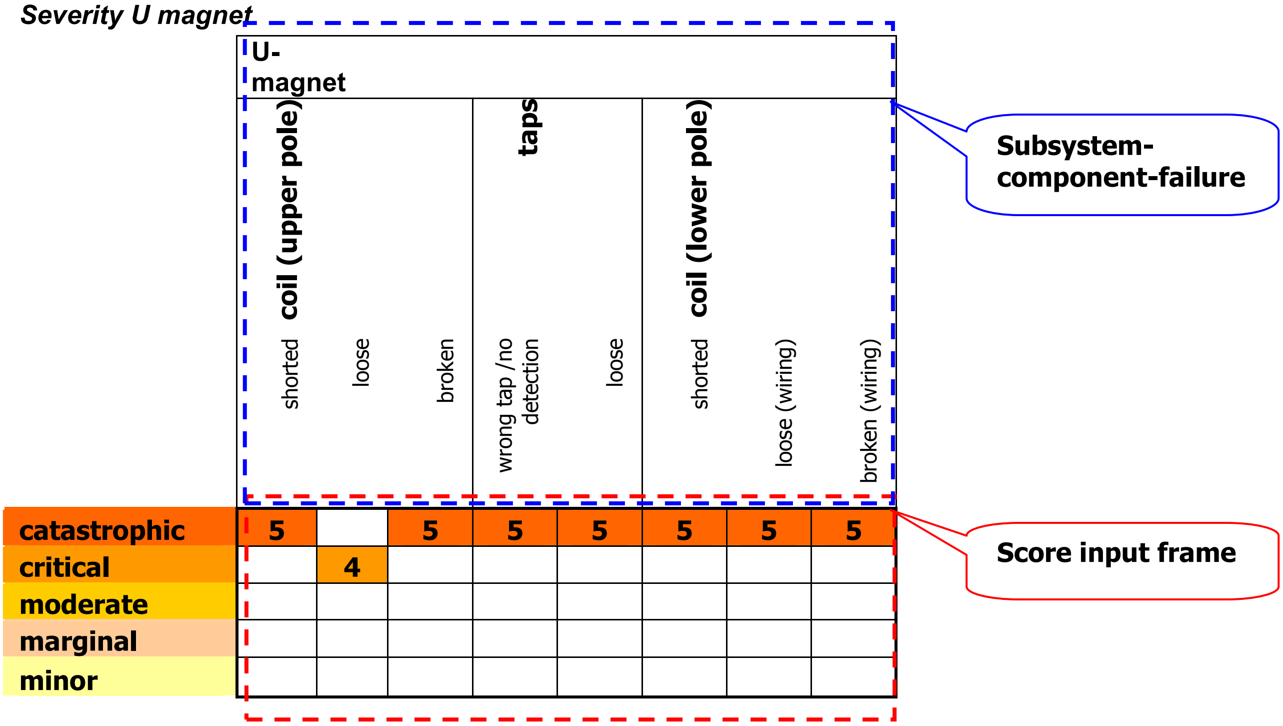


Detection U magnet

	U-magnet							
	coil (upper pole)			**taps**		**coil (lower pole)**		
	shorted	loose	broken	wrong tap /no detection	loose	shorted	loose	broken
Absolute uncertain								
Remote								
Low				**3**				
High	**2**	**2**	**2**		**2**	**2**	**2**	**2**
Almost certain								

Figure 7. Example of a part of an input sheet for one of the scores

The example of the input sheet shows an input frame for a group of components in a subsystem. The descriptive part in the input sheet shows the relationship between causes for failures and components in subsystems. This descriptive part is also used in the severity input sheet. The Severity input sheet is shown below:



Severity U magnet

	U-magnet							
	coil (upper pole)			taps		coil (lower pole)		
	shorted	loose	broken	wrong tap /no detection	loose	shorted	loose (wiring)	broken (wiring)
catastrophic	5		5	5	5	5	5	5
critical		4						
moderate								
marginal								
minor								

Figure 8. Example of a part of an input sheet for one of the scores

Each input is linked to the corresponding column and cell in the detection or severity column of the FMECA sheet. The information about detection and severity can be obtained from the technical documentation.

For the occurrence it is possible to construct the input sheet in the same way. Here this is done directly in the main FMECA sheet. In this case it doesn’t make sense to add a separate input sheet for the occurrence. It would mean that every component should be given an occurrence score by asking a maintenance engineer their experience on each component. The recognized failure modes are observed phenomena. Also, failure modes are properties that can be shared by more components. By asking maintenance engineers their experience in occurrence of failure modes with the mentioned score categories **recurrent, conceivable, sporadic, isolated** or **unlikely** it is possible to give a occurrence score for every component related to the failure mode.

3.3.3. outputs of the FMECA sheet

The IEC 812 standard describes what results can be obtained from the analysis, these are:

- List of detection provisions
- List of failure modes, failure causes and failure effects
- Pareto diagram
- Criticality grid

The list of detection provisions, failure modes, failure causes and failure effects can be extracted from the FMECA sheet easily. It can be done by reading the columns and summarizing them by categories. The Pareto diagram and the Criticality grid are not constructed as the standard prescribes. Normally, a PARETO analysis is carried out on component level. Since the analysis concerns subsystems it is necessary to adapt the calculation method. The criticality grid is normally constructed by evaluation of the probability of failure wit the Severity of a failure. Here the criticality grid is constructed with the occurrence and the severity of a failure mode. Next paragraph explains how this is done.

3.4 Analysis of the FMECA results

The FMECA sheet can be analyzed with two techniques. These are:

- Pareto analysis
- Criticality grid

Both techniques are common used techniques. Here these techniques are adapted to the subsystem approach and the failure mode approach; these will be explained in the next sub paragraphs. The presented approaches are new and developed for the her presented analysis.

3.4.1. Pareto Analysis

The PARETO diagram is mostly a result of a PARETO analysis of all components. A PARETO analysis is an analysis based on the rule that 20 percent of the components are accountable for 80 percent of the failures, the PARETO rule. This analysis is normally carried out on component level. Here it is carried out on subsystem level. The reason for choosing this approach is to make insightful which subsystem is most accountable for the failing of the total system.

For this approach an adaptation of the component RPN's into subsystem RPN's is necessary. Subsystems mostly don't consist of the same amount of components. For this reason the influence of amount of components present in subsystems needs to be discarded. This influence can be discarded in the following way:

- Sum all component RPN's of all components of a particular subsystem.
- Divide the summed components RPN by the number of components in the subsystem and the maximum scores of Detection, Occurrence and Severity.
- Multiply the total score with scale factor 100

This results in in the following equation:

$$RPN_w = \frac{\sum_{c=1}^{c=n} RPN_c}{n \times 125} \times 100 \qquad \textbf{(eq.6)}$$

n : Number of components
125 : maximum score of Detection, Occurence and Severity (=5)

The separate calculation of subsystem RPN's and arranging them with the PARETO technique results in PARETO diagram. The following example shows a result table and PARETO diagram of a system:

Table 8. example of a weighted RPN table

weighted			cumulative
Category	RPN shares	percentages	percentages
Subsystem 1	24	31%	31%
Subsystem 2	21	27%	59%
Subsystem 3	15	19%	78%
Subsystem 4	12	16%	94%
Subsystem 5	5	6%	100%

Remark: the table is an result of a fictitious system

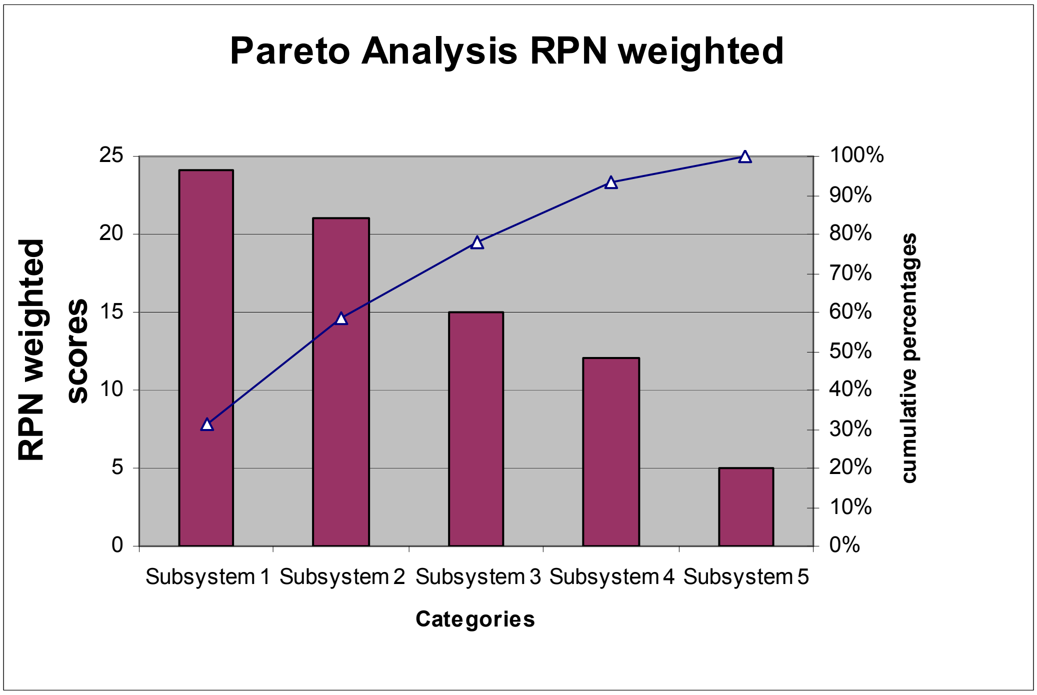


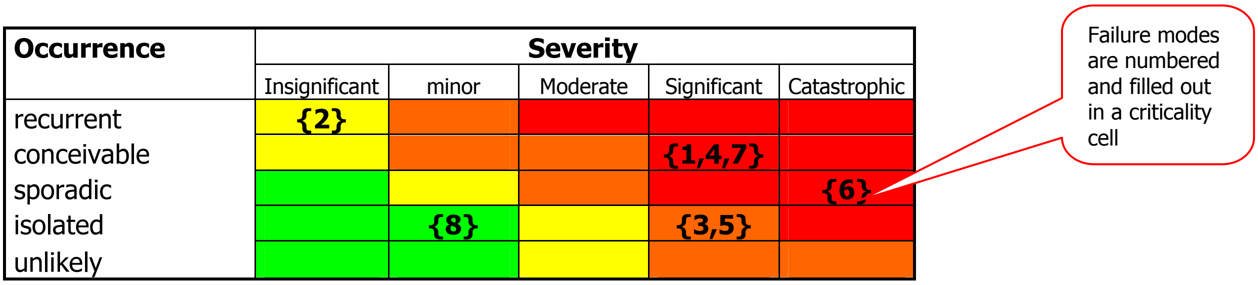
Figure 9. Example of PARETO diagram of a fictitous system

3.4.2. Criticality grid

The criticality grid is a method to indicate which components are most likely to fail and what effect this failing has on the total system. It has its use in the decision process of taking corrective actions. Criticality grids are mostly constructed by plotting probability of failures and the severity of the failure. This way construction is common for the quantitative approach. The IEC812 standard does not prescribe a standard method for constructing a criticality grid, so it is possible to construct the criticality grid with other parameters than probability of failure and the severity of a failure. Here, the parameters used for the criticality grid here, are:

- The Occurrence score of the failure mode.
- The Severity score of the failure mode.

This setup of the developed criticality grid gives insight in the occurrence of failure modes and the severity related to these failure modes. The occurrence is a variable input so when a failure mode's occurrence is increasing; its criticality will increase too. The next figure shows a criticality grid based on these parameters:



Occurrence	Severity				
	Insignificant	minor	Moderate	Significant	Catastrophic
recurrent	🟨 {2}	🟧	🟥	🟥	🟥
conceivable	🟨	🟧	🟧	🟥 {1,4,7}	🟥
sporadic	🟩	🟨	🟧	🟥	🟥 {6}
isolated	🟩	🟩 {8}	🟨	🟧 {3,5}	🟥
unlikely	🟩	🟩	🟨	🟧	🟧

Failure modes are numbered and filled out in a criticality cell

Figure 10. Example of criticality grid

The criticality grid here shows also here a 5 level score for each parameter. The way of ranking Criticality is multiplying the failure mode Occurrence score with the failure mode Severity score. The following formula explains this:

Criticality of a failure mode: $$Criticality = O_{fm} \times S_{fm} \qquad \textbf{(eq.7)}$$

O_{fm} : Occurrence score of a failure mode
S_{fm} : Severity score of a failure mode

The maximum outcome is 25 (5x5) and the minimum outcome is 1 (1x1). The criticality grid parameters concern the criticality of failure modes. This means that all Occurrence scores are analyzed on the average score outcome of components that are related to failure modes. This is done in likewise for the Severity, all Severities are analyzed on the average score outcome of components. This is described by the following formulas:

Severity of a failure mode: $$S_{fm} = \frac{\sum_{c=1}^{c=n} S_c}{n} \qquad \textbf{(eq.8)}$$

S_{fm} : Severity score of a failure mode
S_c : Severity score of the component related to the failure mode
n : number of components related to the failure mode

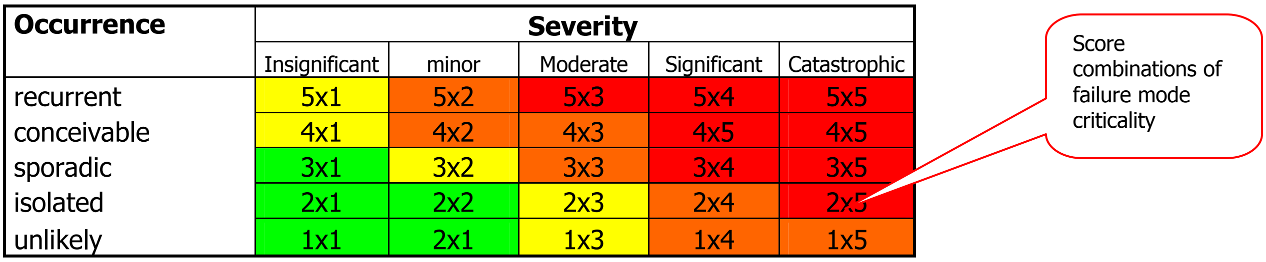
Occurrence of a failure mode: $$O_{fm} = \frac{\sum_{c=1}^{c=n} O_c}{n} \qquad \textbf{(eq.9)}$$

O_{fm} : Occurrence score of a failure mode
O_c : Occurrence score of the component related to the failure mode
n : number of components related to the failure mode

The calculation of the average of severities and occurrences of failure modes can result in numbers with fractions. To make these fractions fit for a 5 level score, a round off rule is applied.

- Fractions ≥0.5 are rounded to 1
- Fractions <0.5 are rounded to 0

The 5 level score in the criticality grid can be maintained in this way. The following criticality grid shows how the 25 criticality outcome combinations of **O_{fm}** x **S_{fm}** are put into the grid.



Occurrence	Severity				
	Insignificant	minor	Moderate	Significant	Catastrophic
recurrent	5x1	5x2	5x3	5x4	5x5
conceivable	4x1	4x2	4x3	4x5	4x5
sporadic	3x1	3x2	3x3	3x4	3x5
isolated	2x1	2x2	2x3	2x4	2x5
unlikely	1x1	2x1	1x3	1x4	1x5

Score combinations of failure mode criticality

Figure 11. Example of criticality grid with outcome combinations

Some combinations are colored differently though the outcome is the same. This should be interpreted in the following way:

> Outcome 3x4 is the same as outcome 4x3, when looking at the formula (eq.3) it is clear that the failure mode occurrence and the failure mode severity differ in score. The color indicates that the importance is set on severity of failure modes.

4 Analysis on failure behavior of e.m. protective relays

4.1. system definition

4.1.1 Analyzed protective relay

The analyzed system is an over current relay with a system setup as manufactured by ABB and General Electric. Specific types are ABB CO-series and GE I/JFC series. The relay is a single phase over current protective relay with time delay and instantaneous unit. The motivation for choosing this type of relays (GE-I/JFC, ABB-CO) is:

- This setup is constructed with an induction disk actuation part and an armature attracted actuation part. (contains most common features of e.m. protective relays)
- The availability of technical brochures and related documents motivates the choice for this type.

The gathered documentation covers the following information categories:

1. System structure
2. System initiation, operation, control and maintenance
3. System environment

Categories 1 and 2 are covered by the use of instruction [10] and adjustment [9] manuals. As a reference for category 2, also interviews with maintenance engineers have been conducted. The system environment is recognized as a dry to humid (rarely damp), clean (minor dust presence) environment.

The relay is designed for continuous operation and is used as for medium voltage feeder and transformer protection. This induction disk relay is on the market since the late 70s. The figures below show the analyzed electromechanical protective relay and it's location in a schematic:

Figure 12. GE relay 12IFC53B1A

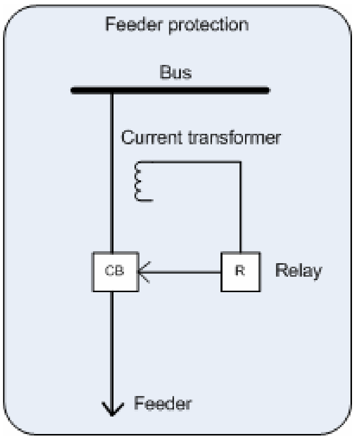


Figure 13. Schematic location of relay

The document "Adjustment techniques for electromechanical relays" gives a more detailed description of the relay. The relay is composed of the following parts:

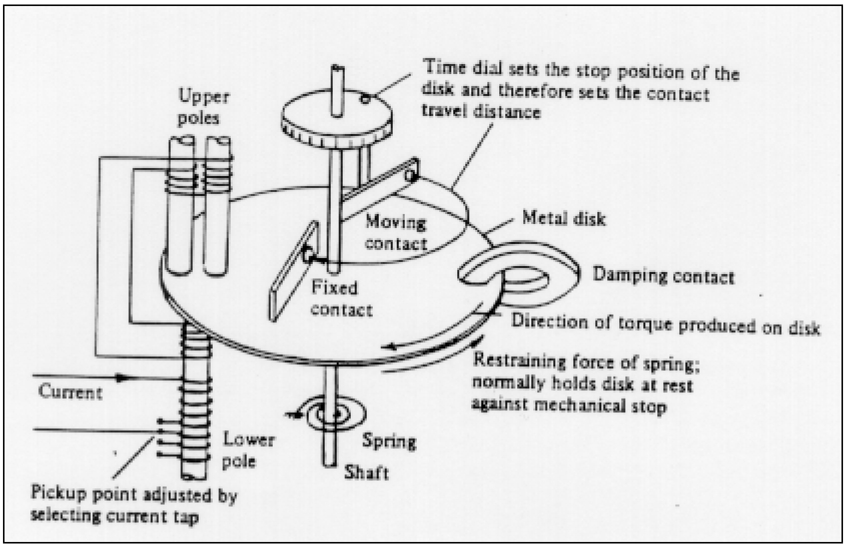
- Disc stop arm
- Stationary contact & zero time dial
- Disc centering and end play
- Time dial
- Drag magnet
- Seal in unit
- Instantaneous unit
- Disk
- Support mold

- Casing

A similar description of system parts can be found in the "ABB descriptive bulletin 41-101E" [10]. Protective relays like the I/JFC series are part of combination of a circuit breaker + protective relay + measurement transformers. The protective relay is connected via a current- or voltage transformer with the feeder and via the trip circuit with the circuit breaker. In the FMECA procedure only the protective relay is submitted to further analysis.

4.1.2. Short description of the principle of operation

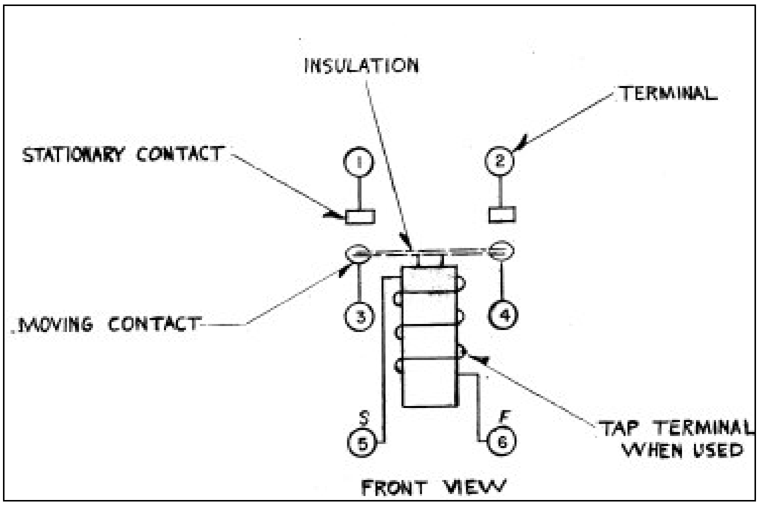
The analyzed system consists of main and backup system. The main system operates on an induction disk principle. The backup system is a so called armature type relay. The following figures illustrate the principle of operation of these two different types of systems. The added descriptions explain briefly how the systems operate.



Current flows into the two coils, poles, that create a magnetic flux. This magnetic flux is induced in the metal disk. The interactions of these two fluxes generate a torque that will cause the disk to travel thus closing the trip circuit by the closure of the moving contact with the stationary contact.

Figure 14. Common schematic setup of an induction unit

The instantaneous unit, the backup relay, and also the seal in unit have a different principle of operation. The figure below illustrates this.



Current passes the coil on terminal 5 and 6. This creates a magnetic field which exerts a force on the armature. The armature travels when an over current occurs and closes the moving contact with the stationary contact. This closes the trip circuit of the circuit breaker.

Figure 15. Common schematic setup of an instantaneous unit

4.2. Developed functional block diagram and subsystem decomposition

The following functional block diagram of an electromechanical protective relay has been developed in order to make a distinction between the purposes of subsystems that form an e.m. protective relay. An electromagnetic protective relay can be described by four basic processes:

- Time setting & Calibration
- Detection
- Actuation
- Tripping

The diagram below shows the relationships between the four processes:

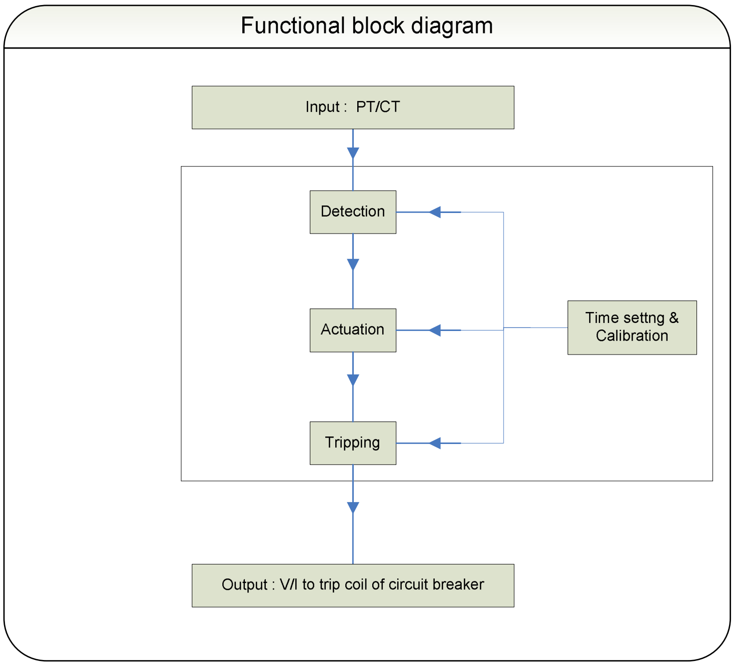


Figure 16. Basic functional diagram of a protective relay

The time setting & calibration process has a strong influence on the 3 other processes. The splitting up of the system in 4 processes helps to give insight in which part of the relay failures occur. So it is possible to determine where the effort of maintenance should be set.

Also a reliability block diagram can be constructed. A reliability block diagram shows the influence of sub processes on the main process. A reliability block diagram of a protective relay can be constructed as follows:

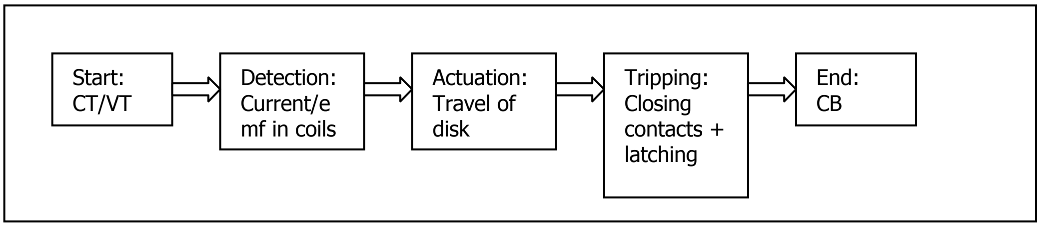


Figure 17. Basic reliability block diagram of a protective relay

The figure shows that the reliability block diagram of a protective relay is a series model[1]. This means that all functional processes form a chain wherein every step has a direct influence on the reliability.

Two statements can be made according to this:

- The weakest subsystem determines the reliability of the whole system.
- All subsystems have to operate to ensure functional operation of the whole system.

Reliability of series systems can be calculated with:

$$R_s = \prod_{i=0}^{n} R_i \tag{10}$$

With:
n= number of elements
Rs= reliability of the system
Ri= reliability of the ith element

Rewritten for diagram 2:

$$R_s = R_d \bullet R_a \bullet R_t \tag{11}$$

With:
R_d = reliability of subsystem detection
R_a = reliability of subsystem actuation
R_t = reliability of subsystem tripping

To determine the separate reliabilities of all subsystems it is necessary to recognize failure mechanisms and to quantify these failure mechanisms. These failure mechanisms can be for example:

- Time delayed.
- Gradual.
- Sudden.

Time delayed and gradual based failure mechanisms can be observed by maintenance engineers. It depends on the skill of the engineer whether this is recognized.

Remarks: 1) Inside the three recognized subsystems some parallel processes can be found. A component level reliability model will show this. The herein presented subsystem approach gives a series model as a result.

4.3. Decomposition of the system into subsystems and subsystem elements

The chosen setup, described in the former paragraph, can be decomposed into subsystems. The decomposition can be carried out by using the terminology of the functional block diagram. This results in the following figure:

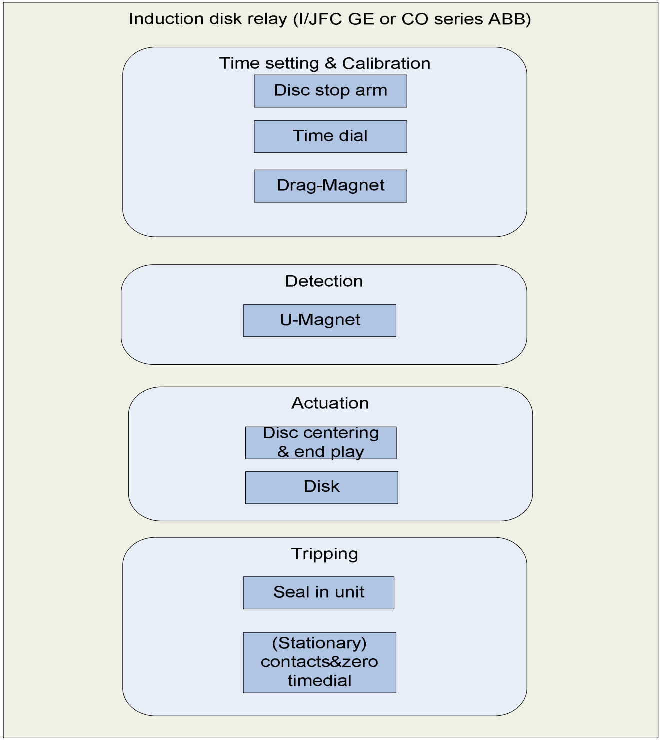


Figure 18. Decomposition of subsystems of a induction disk relay

The four process description is applicable to other existing relay setups as described in [5].

One system has not been submitted to the former figure. A subsystem like an instantaneous unit is actually also a protective relay and has also a similar subsystem decomposition. In this case the actuation subsystem is different. Here, the actuation subsystem consists of an armature. Other differences are the simpler setup of the whole system. The figure below shows the overview of subsystems of the instantaneous unit.

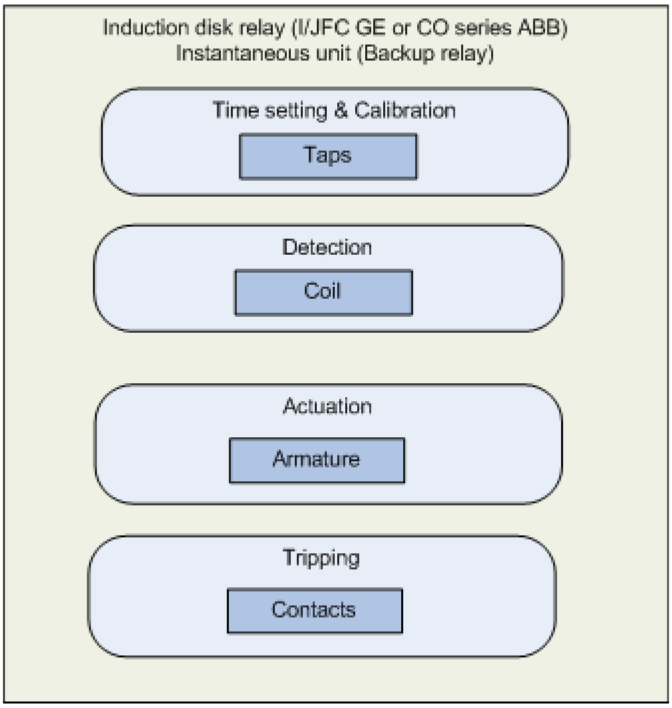


Figure 19. Decomposition of subsystems of an instantaneous unit

A further decomposition of the subsystems results in a total overview of subsystems and their associated components. The result of this decomposition results in the following overviews.

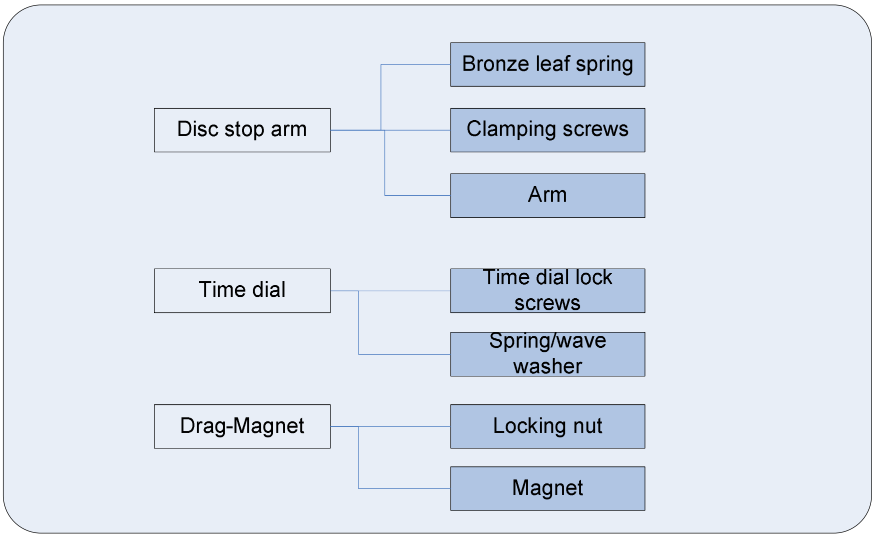


Figure 20. Overview of subsystem "time setting and calibration" and its related components

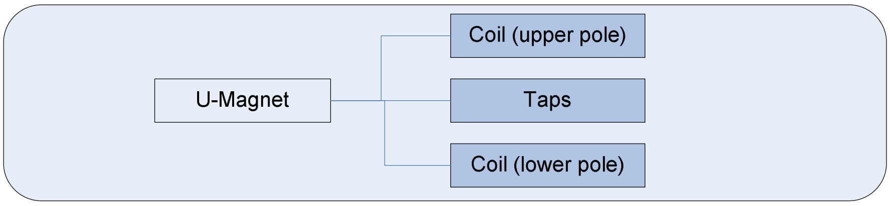


Figure 21. Overview of subsystem "Detection" and its related components

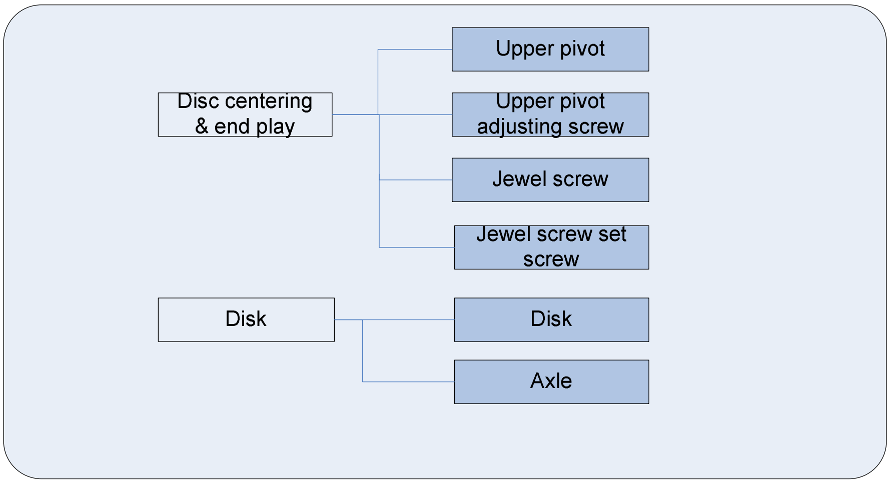


Figure 22. Overview of subsystem "Actuation" and its related components

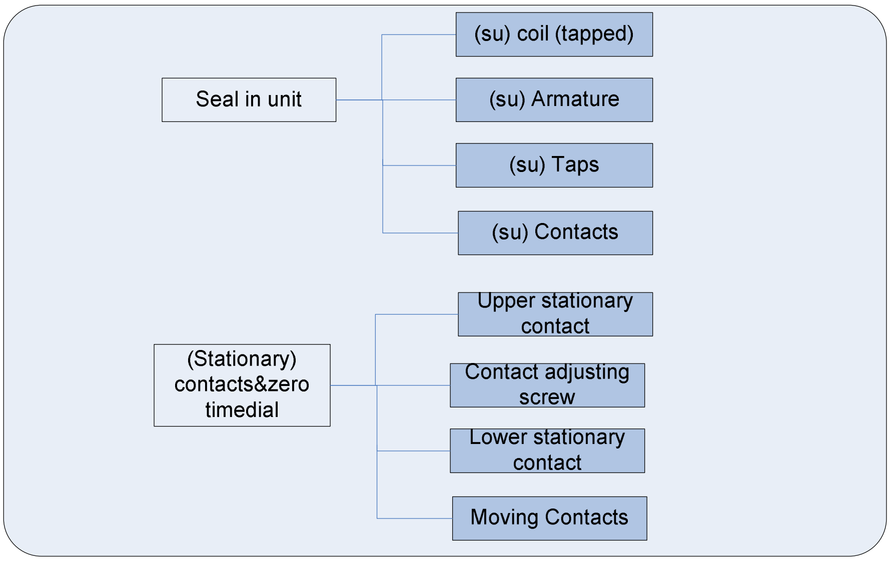


Figure 23. Overview of subsystem "Tripping" and its related components

These overviews form the basis on which FMECA procedure is carried out. The FMECA sheet in appendix 2 is based on the described subsystems and components.

4.4. Failure modes, causes and effects

The identification of failure modes, causes and their effects resulted in a list of 54 events in 21 components of which an overview can be found in the FMECA sheet in appendix 2. These events are summarized into 10 failure modes with 11 general causes and 4 end effects. The following figure shows the relationships between causes, failure modes and end effects.

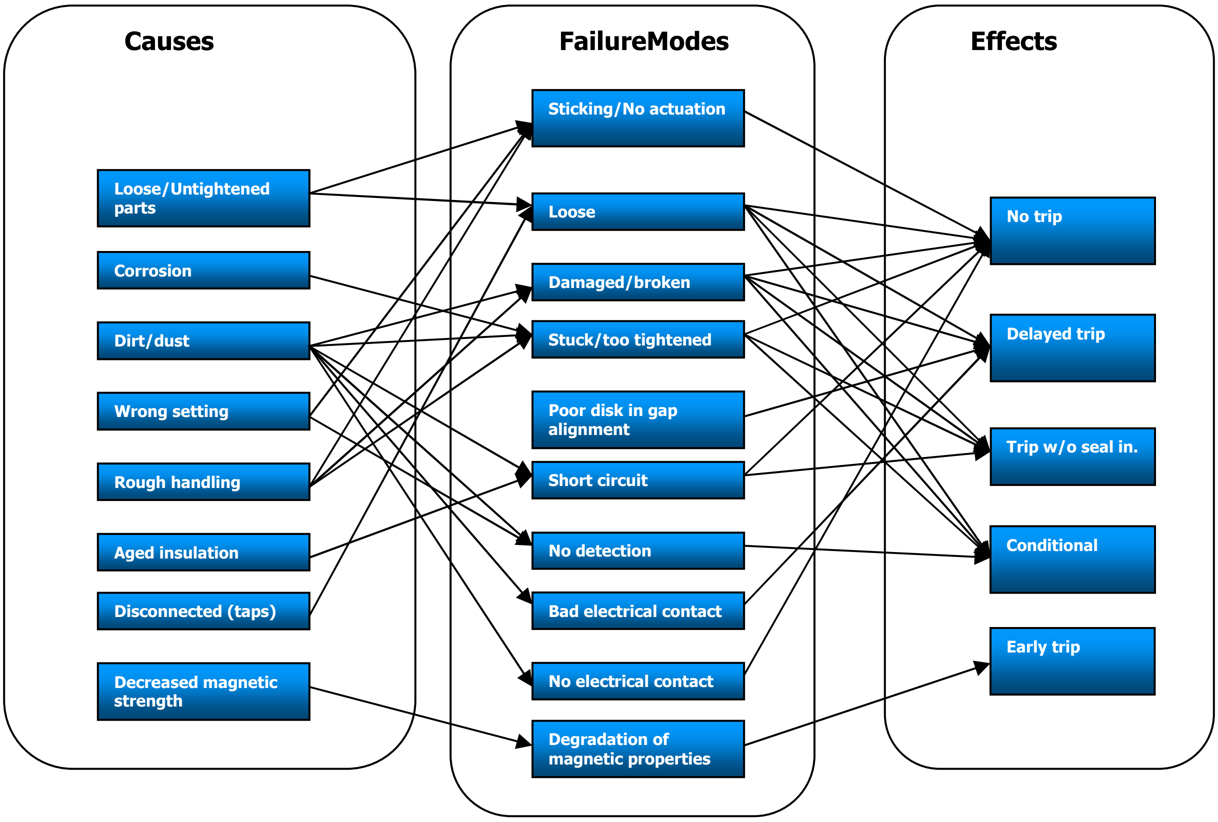


Figure 25. Failure causes, failure modes and potential effects of an induction disk relay

The failure effects explain in which way a failure mode affects the operation of a protective relay. The function of a protective relay is to energize the trip circuit of a circuit breaker. This will cause the circuit breaker to isolate the faulted line. The failure effects as described in the table above are defined as follows:

Table 9. Descriptions of failure effects

Failure effect	Description
No trip	System does not generate a trip signal. Circuit breaker does not act in fault situation.
Delayed trip	System generates a trip signal but not within required time constraint. Circuit breaker acts on trip signal but is stressed longer.
Early trip	System generates a trip signal earlier than the required time constraint. Circuit breaker acts on trip signal.
Trip without seal in	System generates a trip signal but does not energize circuit breaker trip circuit sufficiently. Circuit breaker does not act in fault situation.

These four failure effects can be assigned to general categories, which are useful when defining a performance indicator for protective relays. These categories are:

- Missing operation [No trip, No seal in]
- Unwanted operation [Delayed trip, Early trip]

4.5. Detectability of component failures

Component failures can be detected with the following procedures/means:

- Non invasive visual inspection
- Invasive inspection maintenance (checking components by procedures)
- Functional testing with test sets or other testing means
- Measurement of input and output circuitry
- Inspection of terminals

The next table gives a description of what activities are included in the methods

Table 11. Descriptions of maintenance activities

Maintenance

Inspection:

Visual (non invasive)

- Inspection on dirt, dust or other foreign materials
- Inspection of the insulation of internal leads/wiring
- Checking the settings on the scale
- Checking the flag indication
- Terminal connections

Visual (invasive)

- Checking gaps
- Checking contacts
- Checking pivots and bearings
- Checking moving parts

Mechanical adjustments (invasive)

- Bearings/pivots
- Tightening screws
- Contacts

Auxilliary Measurements

- Wye point measurement input circuitry
- Measurement output circuitry

Functional testing

- Settings
- Pickup/drop out
- Timing (characteristic)
- Instantaneous
- Flag indication / Seal in unit
- Trip circuit test (protectiver relay + circuit breaker) if possible

The detection of component failures depends on the following factors:

- skill of maintenance engineers
- method of detection
- simplicity/complexity of relay setups

An insightful detection method, easy and obvious, results in a unique, unquestionable, interpretation. This is not always the case with detection methods applied in maintenance on e.m. protective relays.

Most failures at e.m. protective relays are detected during the maintenance process. A functional test is mostly carried out as a first step in an inspection. When it passes this test, it is often not needed to take more steps. Sometimes the test shows that relay doesn't operate as the intended setting indicates. A (re)calibration of the settings is in most cases sufficient enough. In other cases other means of detection methods should be used. A setting or (re)calibration procedure can also reveal failure phenomena. However, such a procedure is not intended as a detection method.

The following table shows the methods/techniques and the failures they can detect:

Table 11. Detection of component failure matrix

	Visual inspection (non-invasive)	**Functional test**	**Invasive visual inspection**	**Circuitry measurement**	**Inspection of terminals**
Coils	No	No	Yes	Yes	No
Contacts	No	No	Yes	Yes	No
Wiring (external)	Yes	No		Yes	Yes
(Other)Mechanical parts	No	No	Yes	No	No
Settings	Yes	Yes	No	No	No
Protection up/down	No	Yes	No	No	No
Accessory eqt.	No	Yes	No	No	No

With the application of these methods and the use of the means it is possible to detect all failures.

Remarks:

(1) A functional test determines whether a protective relay operates with the specified settings. An "Up" status indicates that a relay works according to the settings, a "down" status could indicate that the relay doesn't operate according to the settings or a fail to operate.

(2) Case open inspection / maintenance is a labor-intensive measure to find component failures. This measure can only by carried out by well-trained maintenance engineers.

(3) Tightening screws / pulling wiring connections are activities which are carried out at the terminal block, external wiring to the CT's / VT's and other external connections.

(4) The group "mechanical parts" represents the group of broken, bent, damaged, Loose and stuck parts.

(5) Current and voltage transformers are regarded as accessory equipment.

4.6. Analysis of RPN$_w$ and criticality of failure modes

The following paragraphs are based on the information gathered in the FMECA sheet and the input sheets of detection and severity.

4.6.1 Pareto analysis

A method which can be related to the functional block diagram is a Pareto analysis of the subsystem Risk Priority Number (RPN$_W$). This method, described in chapter 3, evaluates all 54 events. Appendix 3 contains the RPN$_w$ calculation tables used for this analysis. The result of this calculation is summarized in the following table:

Table 12. calculated RPN$_w$ of subsystems

Subsystem	RPNw	percentages	cumulative percentages
Detection	24	39%	39%
Tripping	19	30%	68%
Time setting & calibration	13	20%	89%
Actuation	7	11%	100%

With these result the next figure is constructed:

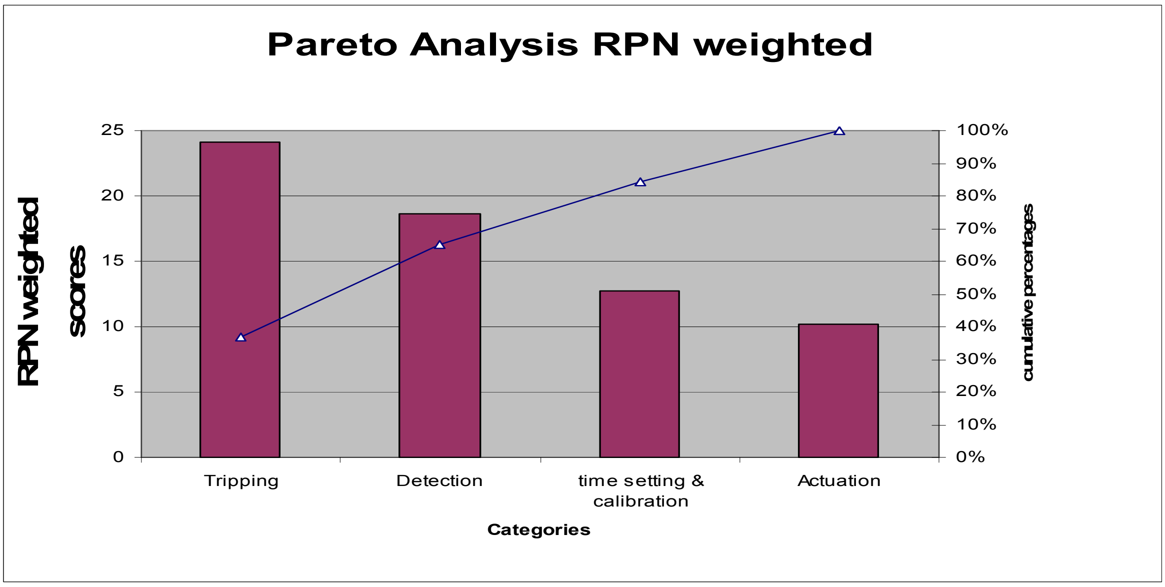


Figure 19. Subsystem Pareto analysis.

The figure shows that components in subsystems **Tripping** and **Detection** require more maintenance attention in comparison to subsystems **Time setting & Calibration** and **Actuation**. This means that when maintenance is focused on components in these subsystems, that most failures can be prevented. According to this analysis the following components should be inspected during maintenance:

Table 13. Crucial components

Subsystem	
Tripping	**Detection**
Tapped coil (su) Contacts (su) Upper stationary contact Lower stationary contact Moving contact	Coil upper pole Coil lower pole Taps

In short it can be said that measurement of input / output circuitry and checking contacts should be part of an inspection.

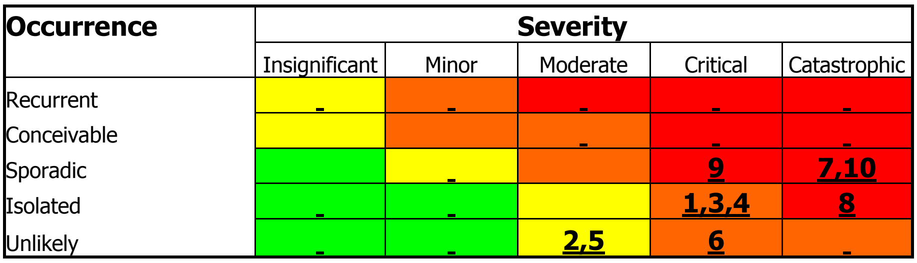
4.6.2. Criticality grid

The criticality grid is constructed by calculating the occurrence (O_{fm}) and the severity (S_{fm}) of a failure mode. The method of calculation is described in chapter 3 and the results of this calculation can be found in Appendix 3. The criticality grid of failure modes is constructed with the values:

Table 14. Occurrence and Severity ranking of failure modes

	Failure modes	**Occurrence score**	**Severity score**
1	No actuation	2	4
2	Decr. Magn. Strength	1	3
3	*Loose*	1	4
4	*Damaged (broken)*	2	With debris=> delayed trip : 4
5	*Stuck / too tightened*	1	No effect if settings ok : 1, else 3
6	*Poor disk alignment*	1	Poorly aligned=>Delayed trip : 4
7	Short circuit	3	5
8	No detection	2	5
9	Bad electrical contact	3	4
10	No electrical contact	3	5

This results in the following criticality grid:



Occurrence	**Severity**				
	Insignificant	Minor	Moderate	Critical	Catastrophic
Recurrent	-	-	-	-	-
Conceivable			-	-	-
Sporadic		-		**9**	**7,10**
Isolated	-	-		**1,3,4**	**8**
Unlikely	-	-	**2,5**	**6**	-

Figure 27. Criticality grid

This criticality grid shows that most failure modes have a criticality in the unsafe direction. The variable factor here is the occurrence of the failure mode. Now failure modes are observed sporadic, when a failure mode is observed more often this would mean that failure mechanisms are influencing the reliable operation of e.m. protective relays. Measures for corrective actions should be taken. Here it means that in the case of an increase observations of failure modes of {1,3,4,6,9,10} the occurrence changes to Conceivable or even Recurrent. Failure modes {9,10} result in an inoperative e.m. protective relay. Failure modes {1,3,4,6} cause delayed trips and can result in the disconnection of a larger area than the faulted area. The backup protection is supposed to take over the function of this e.m. protective relay.

4.7. Review of FMECA suggested detection methods and detection methods in current maintenance practices

Not all detection methods mentioned in the former paragraph are still applied when conducting maintenance on e.m. protective relays. Carrying out activities described in table 11 are part of an approach for keeping the e.m. protective relay in an “As new” condition. Currently, e.m. protective relays are not serviced to an “as new” condition. The current approach no longer includes invasive activities. Main reason for the “case closed” policy is to avoid environmental contamination of the parts (dust, moist, dirt) and to avoid physical contact with sensitive parts. Mechanical parts are not checked anymore. The casing of the e.m. protective relay is only opened when terminals are inside the casing. The table below shows the comparison of the “As new” approach and the “case closed” approach.

Table 15. Comparison of maintenance approaches

“As new” Maintenance	**Current maintenance activities** **(“ Case closed” maintenance)**
Inspection: *Visual (non invasive)* • Inspection on dirt, dust or other foreign materials • Inspection of the insulation of internal leads/wiring • Checking the settings on the scale • Checking the flag indication • Terminal connections *Visual (invasive)* • Checking gaps • Checking contacts • Checking pivots and bearings • Checking moving parts	**Inspection:** *Visual(non invasive)* • Checking the settings on the scale • Checking the flag indication • Terminal connections • Checking contacts
Mechanical adjustments (invasive) • Bearings/pivots • Tightening screws • Contacts	
Auxilliary Measurements • Wye point measurement input circuitry • Measurement output circuitry	*Auxilliary Measurements* • Wye point measurement input circuitry • Measurement output circuitry
Functional testing • Settings • Pickup/drop out • Timing (characteristic) • Instantaneous • Flag indication / Seal in unit • Trip circuit test (protectiver relay + circuit breaker) if possible	**Functional testing** • Settings • Instantaneous • Flag indication / Seal in unit • Trip circuit test (protective relay + circuit breaker) if possible

The visual inspection in the “case closed” approach is a short expert based activity. In some cases, this inspection is not carried out. Circuitry measurement is also applied occasionally. Typical examples where maintenance engineers do open the casing are for example stuck gears in the AEG SD34AK and moving coil elements of timing units. Maintenance procedures on protective relays have become less elaborate since the approach changed from “Case open” to “Case closed” maintenance.

When taking the application of detection methods of current maintenance procedures into account, the detection of component failure matrix can be constructed:

Table 16. Detection of component failure matrix

	Visual inspection (non-invasive)	**Functional test**	**Circuitry measurement**	**Inspection of terminals**
Coils	No	No	Yes	No
Contacts	No	No	Yes	No
Wiring	Yes	No	Yes	Yes
(Other)Mechanical parts	No	No	No	No
Settings	Yes	Yes	No	No
Protection up/down	No	Yes	No	No
Accessory eqt.	No	Yes	No	No

Case closed maintenance results in not being able to notice mechanical component failures. The current maintenance approach is a pragmatic approach that is based on evaluating the functionality of the protective relay. It depends strongly on the skill of engineers whether this functionality evaluation is carried out properly.

5 Proposal for improvement of the acquisition of maintenance process information

5.1. Gathering technical information and defining a condition indication of electro-mechanical protective relays

In the current situation protective relay test forms contain information about the operational status of protective relays. The test procedure consists in most cases at least of a pickup and timing test. The information obtained from testing contains information about pickup / dropout current and time settings. These variables give an indication of the functional status and confirm the correctness of the setting of the protective relay. Additional information about the effort of commissioning the relay is seldom registered in the test report. Such an effort is for example readjusting the time- and magnitude settings of the relay. These remarks are seldom registered and only when the readjustment is done because of a large deviation of the required setting. A fine adjustment is never registered as an additional remark. To find out whether a time elapsing degradation mechanism causes deviating settings of the relay, it is necessary to document this.

5.2. Extracting relevant information by adding automated checklist features

More information about the maintenance activities on e.m. protective relays could be gathered by including the observations and efforts in the test report. Normally such information is documented in the general remarks part of a test report. This is rarely done. The following table shows which subjects are included in current test reports and which subjects should be included extra in a test report for an over current e.m. protective relay:

Table 17. Comparison current test report and proposed test report

In current test report	In proposed test report
• Object information. • Range of settings. • Testing means (power supply set + timing set). • Intended settings (current/time). • Result of zero check (test protective relay as found). • Result of pickup test • Result of time-current characteristics test. • Result of instantaneous pickup test. • Result of target and seal-in operation. • Result of proof test of trip circuit • Outcome of signaling- and trip test. • General remarks	• All subjects in the current test report **Observations:** • Pickup function • Seal-in function • Indication (flag) • Trip circuit test • CB operates on trip • CT/ PT disconnected • Loose Lead(s) • Power supply disconnected • Contact function • Drop-out time meeting requirements **Efforts:** • Adjustment of time settings • Input circuit measurement • Output circuit measurement • Tightening terminal screws • Cleaning contacts

An example of such a test report can be found in appendix 5.

5.3. Framework for documenting registration subjects

To make the current maintenance reports more fit for analysis a new framework for a test report should be developed. The basic format of a test report can remain the same. The test report items (settings, range, flag indication etc), that describe the operational status, are information, which is already available. Information about the observations (flag indication doesn't work, seal in unit didn't seal in), and efforts (tightening screws, cleaning contacts etc), should be added to the format of the test protocol. Normally these subjects would be registered by a textual input. This makes a set of test protocols less fit for numerical analysis when they are collected. With the use of a numerical coding standard the information in the test protocol becomes numerically analyzable. How the coding works is explained in the next figure:

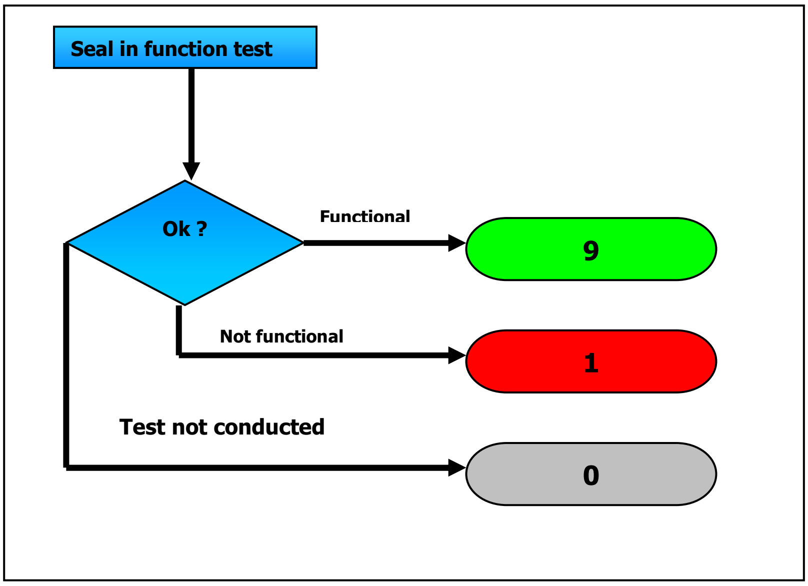
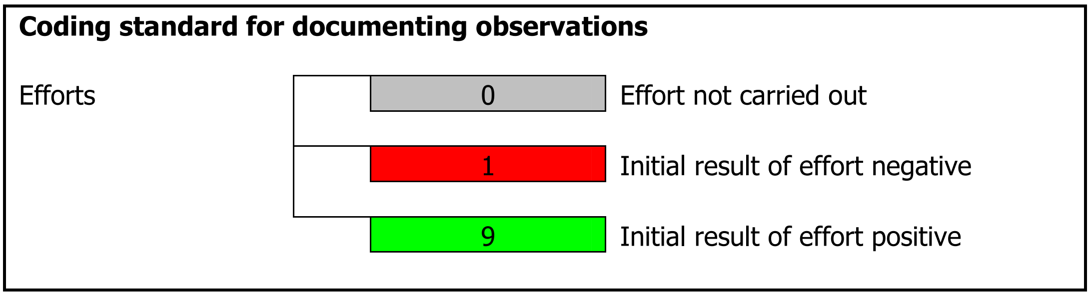


Figure 28. Example of coding a test outcome in a Flow chart

The following coding standard is used for documenting information in the new developed test report:

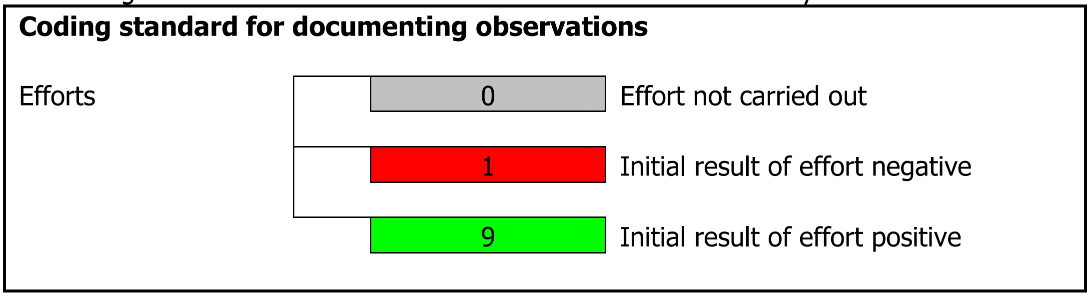


Coding standard for documenting observations

Efforts	0	Effort not carried out
	1	Initial result of effort negative
	9	Initial result of effort positive

Figure 29. Coding standard for documenting information

The coding standard of an observation can be done in the same way:



Coding standard for documenting observations

Efforts	0	Effort not carried out
	1	Initial result of effort negative
	9	Initial result of effort positive

Figure 30. Coding standard for documenting observations

More flow charts like figure 21 can be constructed. The possible inputs {0,1,9} related to the observations and efforts in the proposed test report can be found in appendix 4. The choice for the numbers {0,1,9} is arbitrary. The convenience of the coding standard becomes clearer with the following example:

Example 1.
A protective relay is subjected to a test for checking the seal-in function and doesn't pass this test. The test engineer fixes the problem and the protective relay passes this test. The engineer doesn't write this down in the remark field of the test reportl. In the new test protocol this activity is an item in the checklist. The first observation of the test engineer was a "fail" and is coded "1". The first result of the test is registered. By documenting it like this it is possible to find out how the functional status of the protective relay was when before it was brought back to a functional status.

Test reports also contain information about the overall outcome of the inspection. Mostly this information is documented as "Pass" or "Fail". Also for the outcome a coding standard can be used. The following coding standard is based on the condition indexation used by Nuon.

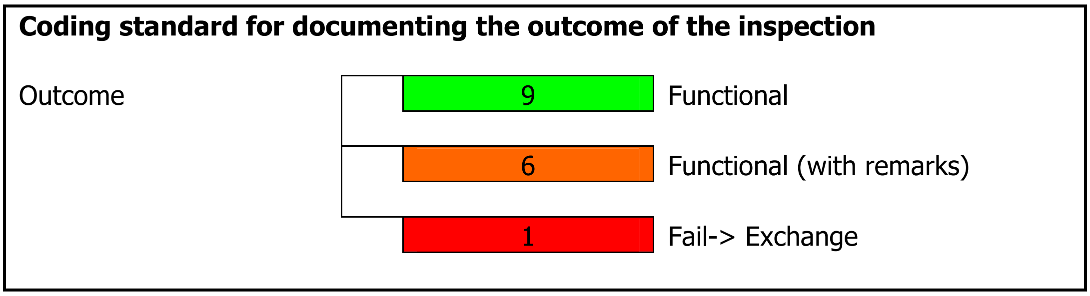
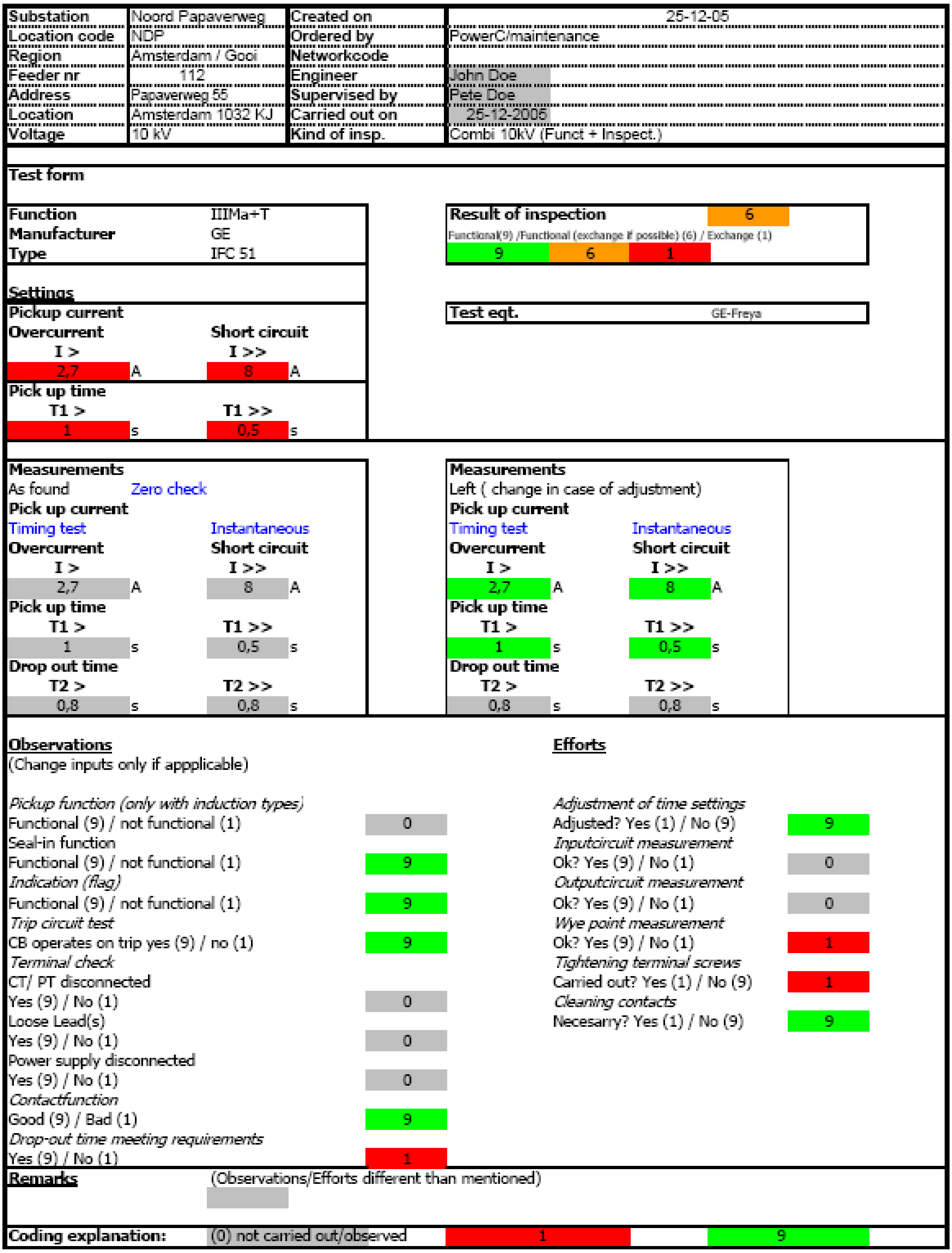


Figure 31. Coding standard for the outcome of the inspection

When the outcomes of inspection of protective relays need to be evaluated the coding also here shows its advantage. This is the case when codes {1} and {6} are used for the end result. In case of

- {1} Exchange has to take place.
- {6} Further analysis required before taking corrective actions.

The implementation of these two coding standards results in the following test report:



Substation	Noord Papaverweg	**Created on**	25-12-05
Location code	NDP	**Ordered by**	PowerC/maintenance
Region	Amsterdam / Gooi	**Networkcode**	
Feeder nr	112	**Engineer**	John Doe
Address	Papaverweg 55	**Supervised by**	Pete Doe
Location	Amsterdam 1032 KJ	**Carried out on**	25-12-2005
Voltage	10 kV	**Kind of insp.**	Combi 10kV (Funct + Inspect.)

Test form

Function	IIIMa+T
Manufacturer	GE
Type	IFC 51

Result of inspection 6

Functional(9) /Functional (exchange if possible) (6) / Exchange (1)

9	6	1

Settings

Pickup current

Overcurrent		**Short circuit**	
I >		**I >>**	
2,7	A	8	A

Pick up time

T1 >		**T1 >>**	
1	s	0,5	s

Test eqt. GE-Freya

Measurements

As found Zero check

Pick up current

Timing test		Instantaneous	
Overcurrent		**Short circuit**	
I >		**I >>**	
2,7	A	8	A
Pick up time			
T1 >		**T1 >>**	
1	s	0,5	s
Drop out time			
T2 >		**T2 >>**	
0,8	s	0,8	s

Measurements

Left (change in case of adjustment)

Pick up current

Timing test		Instantaneous	
Overcurrent		**Short circuit**	
I >		**I >>**	
2,7	A	8	A
Pick up time			
T1 >		**T1 >>**	
1	s	0,5	s
Drop out time			
T2 >		**T2 >>**	
0,8	s	0,8	s

Observations

(Change inputs only if appplicable)

Pickup function (only with induction types)	
Functional (9) / not functional (1)	0
Seal-in function	
Functional (9) / not functional (1)	9
Indication (flag)	
Functional (9) / not functional (1)	9
Trip circuit test	
CB operates on trip yes (9) / no (1)	9
Terminal check	
CT/ PT disconnected	
Yes (9) / No (1)	0
Loose Lead(s)	
Yes (9) / No (1)	0
Power supply disconnected	
Yes (9) / No (1)	0
Contactfunction	
Good (9) / Bad (1)	9
Drop-out time meeting requirements	
Yes (9) / No (1)	1

Efforts

Adjustment of time settings	
Adjusted? Yes (1) / No (9)	9
Inputcircuit measurement	
Ok? Yes (9) / No (1)	0
Outputcircuit measurement	
Ok? Yes (9) / No (1)	0
Wye point measurement	
Ok? Yes (9) / No (1)	1
Tightening terminal screws	
Carried out? Yes (1) / No (9)	1
Cleaning contacts	
Necesarry? Yes (1) / No (9)	9

Remarks (Observations/Efforts different than mentioned)

Coding explanation:	(0) not carried out/observed	1	9

Figure 32. Proposed test report format

The report shows in what condition (functional, not functional) the relay is found and what has been done to make the relay functional again. A more readable format can be found in appendix 5.

This test report is constructed in a spreadsheet program and has a database export sheet. The database export sheet makes it possible to collect the information of test protocols in a database. A standard data collection format for e.m. protective relays makes it possible to analyze different types (brands) for typical information. The new developed test protocol forms the basis for data collection format for over current type relays.

The new developed test protocol contains all information proposed in the manufacturers test protocol and is supplemented with a more convenient way of documenting observations and efforts. The new developed test protocol is organized as follows:

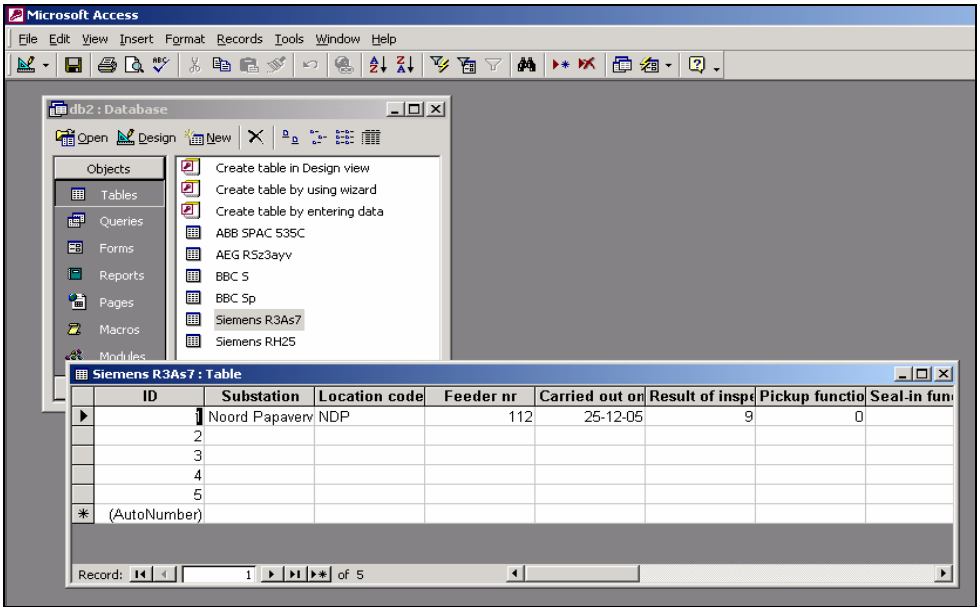
Table 19. Organization of input frames and explanation of their purpose

Input frame	**Purpose**
Input frame for documenting settings as found.	The "As found" condition, results of zero check can be filled out here
Input frame for documenting settings in case of adjustment of settings	The new settings meet the required settings within a tolerance. This tolerance can be read back with this
Input frame for documenting observation and efforts	In case of one or more observations / have been done they should be filled out here. In this way the failure modes related to observations can be evaluated on occurrence so a reassessment of criticality can be made.
Input frame for documenting observations and efforts different from mentioned.	Observations and efforts different from mentioned
Input frame for documenting the end result of the inspection.	Overall result of the whole procedure.

The input frames are constructed with value dependent color input cells. The set of inputs {0,1,9} or {1,6,9} change the color of the input cells. The test report can read back whether observations and efforts are done and documented. The input cells are by default {0} grey and indicate that these observations / efforts are not carried out yet. Not all efforts and observations need to be done to complete the inspection. When a relay passes the timing tests or the zero check, it is not needed to fill out most of the observations input cells. It can be assumed that these observation/efforts need not to be done.

5.4. Analysis of information gathered from the maintenance process.

The earlier discussed data collection format forms the basis of the collection of test protocol results of all similar type protective relays. The uses of a coding standard in the test protocols prove their convenience when analyzing the data in a database. The information in the database can be arranged in such way the information in a way it becomes analyzable. The following picture shows a result of an import of data collection sheets of protective relays.



ID	Substation	Location code	Feeder nr	Carried out on	Result of inspe	Pickup functio	Seal-in fun
1	Noord Papaverv	NDP	112	25-12-05	9	0	
2							
3							
4							
5							
(AutoNumber)							

Figure 33. Example of an import of a test report into a database table

Remarks: the picture above is an example of a fictitious database.

Here, the database is organized in a way that all types over current protective relays are collected in separate tables. In this way it is possible to analyze the results of inspections (Overall Pass/Fail, observations and efforts). Separate or combined queries arrange the information in such a way that trends can be observed. For example, a group of Siemens R3As7 relay shows problems with the seal-in function or problems with pickup.

By means of counting and comparing the results of this group with the results obtained from an earlier inspection it is possible to quantify the results in a trend diagram. An example of such a diagram could be:

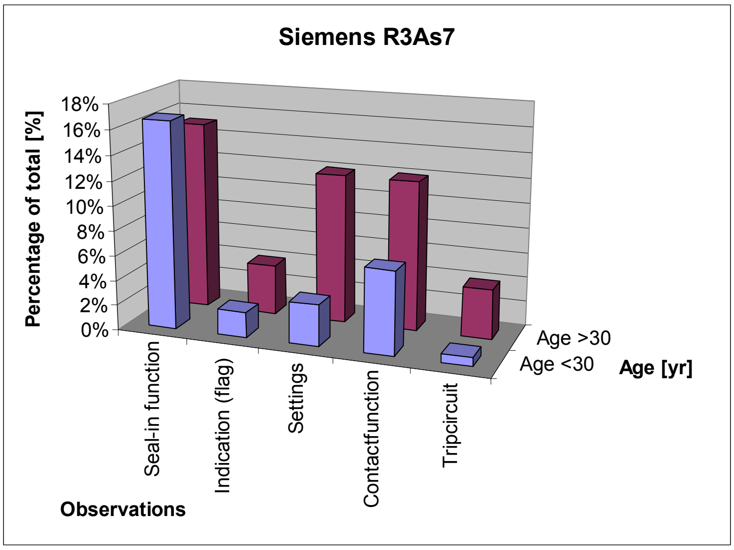


Figure 34. Example of a possible solution to display trends in a group of protective relays.

6 Conclusions and recommendations

Conclusions

Developed FMECA sheet

- A functional block diagram of an electromechanical protective relay has been developed.
- A new quantitative method has been developed for conducting an FMECA. The subsystem approach shows where to concentrate maintenance efforts and is an extension of the basic component approach.
- The use of an uniform five level score throughout the procedure makes scores intuitively comparable.
- The presented FMECA sheet contains all features of a "standard" FMECA sheet, though the adaptation of the standard sheet by following new design rules improved the readability.

Results of the FMECA procedure

- The presented applied detection methods are sufficient for finding component failures, though the success of some of these methods is depending on the skill of the maintenance engineers.
- According to the subsystem PARETO chart attention should be paid to the following subsystem components: Tripping : trip circuitry (coils and contacts)
  Detection: input circuitry (coils and taps)
- The results of the FMECA procedure on e.m. protective relays are based on available documents and interviews with protection specialists and engineers. The interviews have been conducted under six people of two companies. These companies are Siemens Nederland N.V. and Nuon. These companies operate as an engineering/servicing company and as a system operator in this field. During the interviews no contradiction in statements has been found.

Evaluation of the Maintenance process

- E.M. protective relays are no longer serviced to an "As new" condition. Support and replacement parts are hardly or no longer available.
- "Case closed" maintenance is an approach that avoids mechanical component failures by unintended "rough handling" or accumulated "dirt/dust". Mechanical failure due to ageing such as corrosion can't be detected with this approach.
- In the actual situation, maintenance activities on protective relays are documented by a Pass or Fail result of functional testing. This pragmatic way of documenting results in not having information about what is done to keep the e.m. protective relay functional and what phenomena (failure modes) are observed during maintenance.

Proposal for improved acquisition for maintenance process information

- The proposed test report concerns a test report of an over current type protective relay. Test reports for distance- and differential can be constructed in a similar way.
- The proposed test report is organized in way to retrieve information about the condition "As found" and condition "As left".
- The {1,6,9} end result is based on a condition indexing which is used by Nuon. Here this condition indexing is extended by describing general categories of observations and efforts. The observations and efforts are given, in a similar way, a code which makes it fit for use in a numerical data analysis.
- The proposed coding standard makes qualitative inspection results quantifiable for maintenance.

Recommendations

- Electromechanical protective relays will still be in service in the near future. This is mainly due to the large numbers and the low push for replacement of these components. For this reason it is still useful to evaluate these protective relays.
- Current maintenance registration forms are unfit for analyzing failure behavior of e.m. protective relays. Using the proposed test report in Chapter 5, it will be possible to analyze this. The organization of this test protocol makes it possible to acquire more information about failure modes and failure causes.
- Construct a database for protective relays for the collection of data form test protocols.
- Start up a cooperation of more parties in implementing the proposed test report. Sharing and comparing data could lead to improved maintenance approaches on e.m. protective relays.
- Let the maintenance engineer decide the pass or fail of a relay. The coding of observations and efforts could be used to construct a {6} indication in the {1,6,9} inspection outcome of a test protocol.

References

[1] “Gebiedsindeling”, DTE august 2003.

[2] “Questionnaire with participation of 3 TSO’s”, KEMA.

[3] “Betrouwbaarheid @ Vision”, Phase to Phase April 2001, document 01-119 pmo

[4] “Incorporation reliability calculations in routine network planning: theory and practice”, paper 0025 18th International conference on electricity distribution by J.G. Slootweg (Essent Netwerk B.V.) and P.M. van Oirsouw (Phase to Phase)

[5] “Advies van de Energieraad over aansprakelijkheid bij leveringsonderbrekingen”, Algemene Energieraad, October 2003.

[6] “Rapport voor Algemene Energieraad: Achtergronden bij aansprakelijkheid bij onderbrekingen van elektriciteitsvoorzieningen”, Kema Consulting April 2003, summary pp iii-v

[7] “Gansch het raderwerk staat stil – De kosten van stroomstoringen”, SEO 2003, report no 685, ISBN 90-6733-243-7, pages iii-iv

[8] “Analysis techniques for system reliability-Procedure for failure mode effects analysis”, IEC 812 premiere edition 1985

[9] “Adjustment techniques for electromechanical relays GEK99350, General electric http://www.geindustrial.com/products/support/emrelays/gek99350.pdf

[10] “ABB descriptive bulletin 41-101E”, ABB http://library.abb.com/GLOBAL/SCOT/scot229.NSF/VerityDisplay/7A0FC5352A412E69C1256E7800548916/$File/DB41_101e_CO.pdf
and
http://www.abb.com/global/abbzh/abbzh251.nsf!OpenDatabase&db=/global/seitp/seitp328.nsf&v=9AAC720001&e=us&c=95301E2F0C12B5CBC1256E7E003223E5

List of abbreviations

e.m.	:	electromechanical
FMEA	:	failure mode effects analysis
FMECA	:	failure mode effect and criticality analysis
RPN	:	Risk Priority Number
TSO	:	Transmission system operator
LNO	:	Local network operator

List of definitions

Outage	network interruption resulting in disconnection of customers
Impact of an outage	the way in which an interruption affects customers
Cascaded outage	interruption which affects a larger area (group of customers) than only the intended protected area
Risk Priority Number	ranking that combines scores
PARETO analysis	technique for arranging scores by the weight of scores
PARETO rule	rule that states that 80 percent of the failures is caused by 20 percent of the components
Failure mode	the effect by which a failure is observed in a system component
Failure effect	the way a failure affects the operation of a system
Status	condition parameter that indicates the state of operation of the relay.
Condition indicator	indicator, which describes the maintenance efforts, put into the component to result in operational status.
Maintenance effort	actions required for status verification and keeping the component in service.
Test report	report wherein test results and maintenance activities are documented

Appendix

A1 Explanation of common protective relaying principles

The following passage gives a brief explanation of the following protective relaying schemes in Dutch medium voltage grids:

- over current protection,
- differential protection
- distance (zone) protection

The figures and descriptions are taken from the following documents:

- "Electrical engineering handbook" by Wai Kai Chen, chapter 9
- "Art and Science of protective relaying" by R. Mason

Over current protection

The following picture shows a radial feeder consisting of three sections.

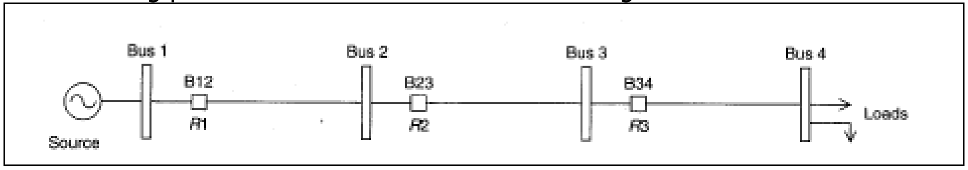


Figure 1. Radial feeder

Each circuit breaker B is tripped by a protective relay which operates according to the inverse time curve as shown below:

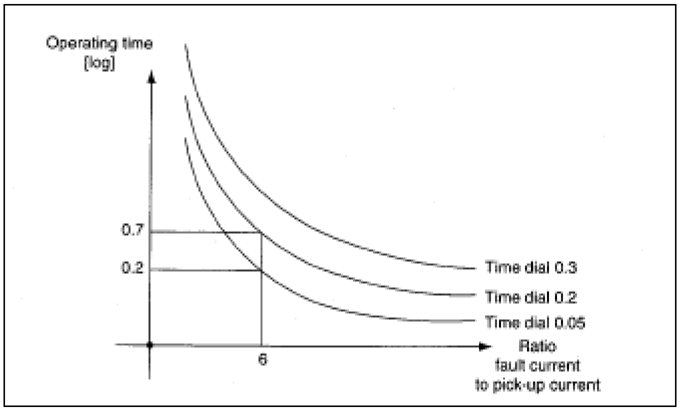


Figure 2. Inverse time curves

Here three circuit breakers are tripped on 5A fault current. The curves show that the three circuit breakers trip on different moments. The example here gives an operating time of 0.2 and 0.7. One circuit breaker will trip on a later instance. In this way backup protection is realized. Here circuit breaker B12 is the backup for B23 and 34. And circuit breaker B23 is the backup of B34.

Differential protection

(Current) Differential protection consist of an over current type relay and two interconnected current transformers. The protected element here is a portion of a bus.

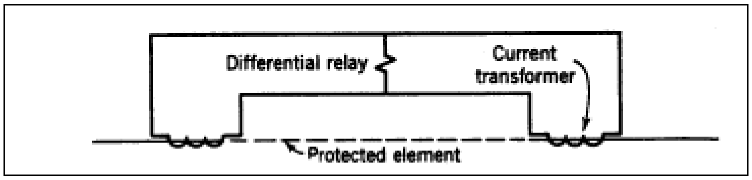


Figure 3. basic setup current differential

The differential protection only protects the bus portion between the current transformers. A fault in an adjacent section will not cause this setup to trip the circuit breaker. The currents flowing through the current transformers circulate but do not flow through the relay.

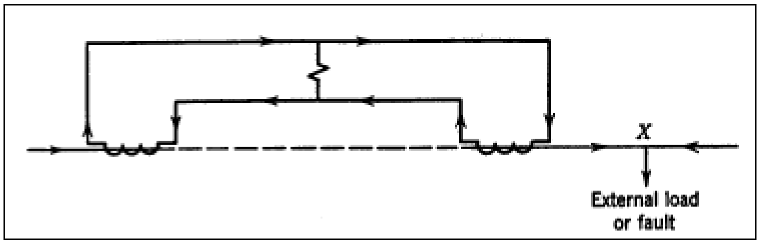


Figure 4. External fault

A fault in the protected section, an internal fault, will cause the differential relay to trip the circuit breaker.

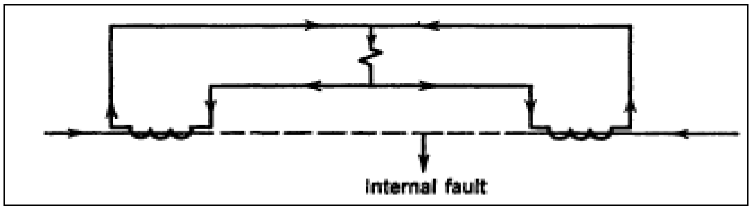


Figure 5. External fault

Distance (impedance) protection
This protective relay is operates on the voltage-current ratio or impedance principle. Impedance is an electrical measure of transmission line or bus. The operation characteristic is shown below.

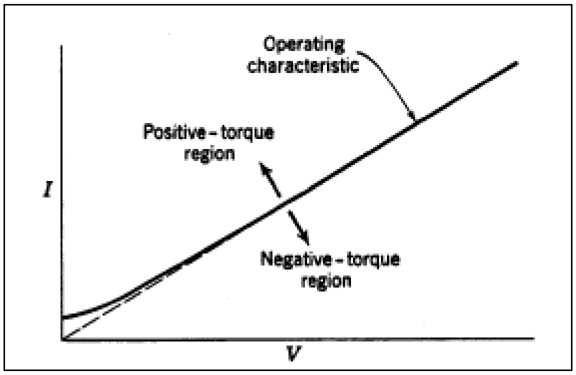


Figure 6. operation characteristic impedance relay

The impedance relay is a balanced unit. A change in voltage or in current causes the impedance to change thus changing the balance. The figure below shows what happens when the balance is disturbed:

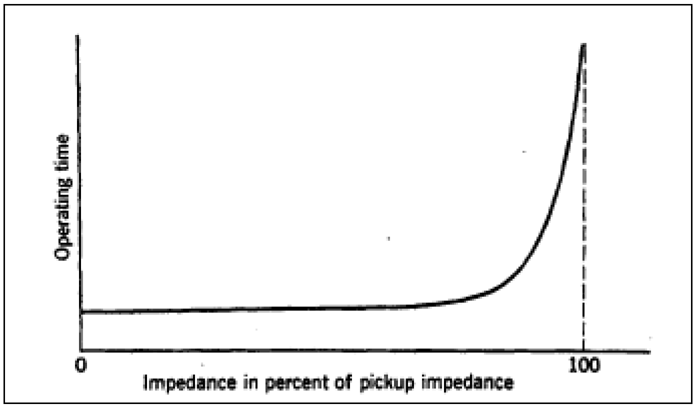
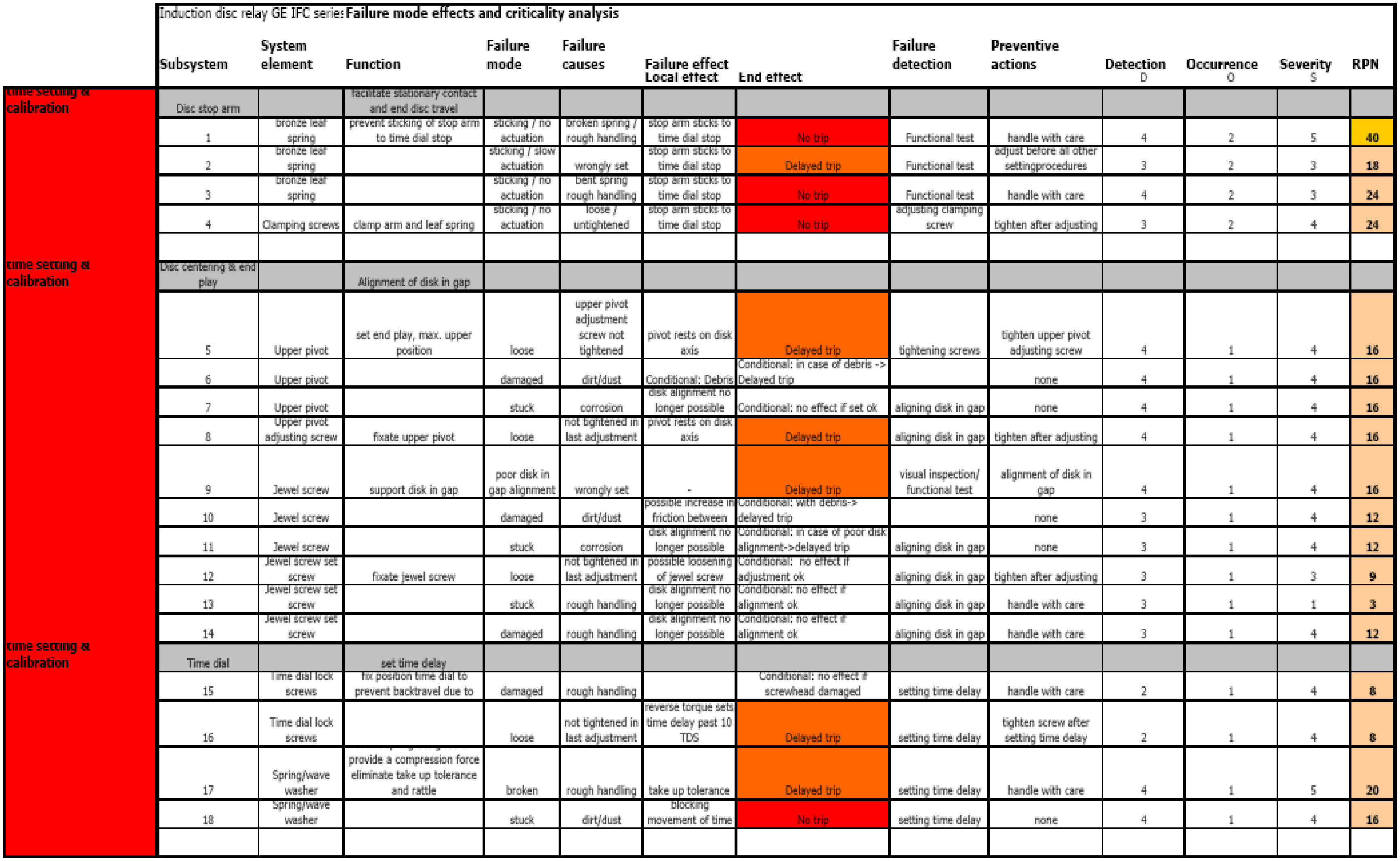


Figure 6. operation time versus impedance characteristic

A change in impedance is related to a time to trip. The protective relay operates instantly at short circuit situations and time delayed in case of an overload.

A2 FMECA sheet and input sheets (Detection, Severity)



Induction disc relay GE IFC serie **Failure mode effects and criticality analysis**

	Subsystem	System element	Function	Failure mode	Failure causes	Failure effect Local effect	End effect	Failure detection	Preventive actions	Detection D	Occurrence O	Severity S	RPN
time setting & calibration	Disc stop arm		facilitate stationary contact and end disc travel										
	1	bronze leaf spring	prevent sticking of stop arm to time dial stop	sticking / no actuation	broken spring / rough handling	stop arm sticks to time dial stop	No trip	Functional test	handle with care	4	2	5	**40**
	2	bronze leaf spring		sticking / slow actuation	wrongly set	stop arm sticks to time dial stop	Delayed trip	Functional test	adjust before all other settingprocedures	3	2	3	**18**
	3	bronze leaf spring		sticking / no actuation	bent spring rough handling	stop arm sticks to time dial stop	No trip	Functional test	handle with care	4	2	3	**24**
	4	Clamping screws	clamp arm and leaf spring	sticking / no actuation	loose / untightened	stop arm sticks to time dial stop	No trip	adjusting clamping screw	tighten after adjusting	3	2	4	**24**
time setting & calibration	Disc centering & end play		Alignment of disk in gap										
	5	Upper pivot	set end play, max. upper position	loose	upper pivot adjustment screw not tightened	pivot rests on disk axis	Delayed trip	tightening screws	tighten upper pivot adjusting screw	4	1	4	**16**
	6	Upper pivot		damaged	dirt/dust	Conditional: Debris	Conditional: in case of debris -> Delayed trip		none	4	1	4	**16**
	7	Upper pivot		stuck	corrosion	disk alignment no longer possible	Conditional: no effect if set ok	aligning disk in gap	none	4	1	4	**16**
	8	Upper pivot adjusting screw	fixate upper pivot	loose	not tightened in last adjustment	pivot rests on disk axis	Delayed trip	aligning disk in gap	tighten after adjusting	4	1	4	**16**
	9	Jewel screw	support disk in gap	poor disk in gap alignment	wrongly set	-	Delayed trip	visual inspection/ functional test	alignment of disk in gap	4	1	4	**16**
	10	Jewel screw		damaged	dirt/dust	possible increase in friction between	Conditional: with debris-> delayed trip		none	3	1	4	**12**
	11	Jewel screw		stuck	corrosion	disk alignment no longer possible	Conditional: in case of poor disk alignment->delayed trip	aligning disk in gap	none	3	1	4	**12**
	12	Jewel screw set screw	fixate jewel screw	loose	not tightened in last adjustment	possible loosening of jewel screw	Conditional: no effect if adjustment ok	aligning disk in gap	tighten after adjusting	3	1	3	**9**
	13	Jewel screw set screw		stuck	rough handling	disk alignment no longer possible	Conditional: no effect if alignment ok	aligning disk in gap	handle with care	3	1	1	**3**
	14	Jewel screw set screw		damaged	rough handling	disk alignment no longer possible	Conditional: no effect if alignment ok	aligning disk in gap	handle with care	3	1	4	**12**
time setting & calibration	Time dial		set time delay										
	15	Time dial lock screws	fix position time dial to prevent backtravel due to	damaged	rough handling		Conditional: no effect if screwhead damaged	setting time delay	handle with care	2	1	4	**8**
	16	Time dial lock screws		loose	not tightened in last adjustment	reverse torque sets time delay past 10 TDS	Delayed trip	setting time delay	tighten screw after setting time delay	2	1	4	**8**
	17	Spring/wave washer	provide a compression force eliminate take up tolerance and rattle	broken	rough handling	take up tolerance	Delayed trip	setting time delay	handle with care	4	1	5	**20**
	18	Spring/wave washer		stuck	dirt/dust	blocking movement of time	No trip	setting time delay	none	4	1	4	**16**

Induction disc relay GE IFC serie **Failure mode effects and criticality analysis**

	Subsystem	System element	Function	Failure mode	Failure causes	Failure effect Local effect	End effect	Failure detection	Preventive actions	Detection D	Occurrence O	Severity S	RPN
Detection	U-magnet		create emf in coils										
	19	Coil (upper pole)	create/induce emf in disc	short circuit	aged insulation	-	No trip	measurement of coilresistance	none	2	3	5	**30**
	20	Coil (upper pole)		short circuit	dirt/dust	-	No trip	measurement of coilresistance	none	2	3	5	**30**
	21	Coil (upper pole)		loose	rough handling	-	No trip	measurement of coilresistance	handle with care	2	4	4	**32**
	22	Coil (upper pole)		broken	rough handling	-	No trip	measurement of coilresistance	handle with care	2	4	5	**40**
	23	Taps	set magnitude of detection current	no detection	wrongly set	-	No trip	functional test	compare with tapsetting main unit	3	2	5	**30**
	24	Taps		loose	disconnected	-	No trip	Check connections	check connections after disconnection	2	2	5	**20**
	25	Coil(lower pole)	create/induce emf in disc	short circuit	aged insulation	-	No trip	measurement of coilresistance	none	2	3	5	**30**
	26	Coil(lower pole)		short circuit	dirt/dust	-	No trip	measurement of coilresistance	none	2	3	5	**30**
	27	Coil(lower pole)		loose	rough handling	-	No trip	measurement of coilresistance	handle with care	2	3	5	**30**
	28	Coil(lower pole)		broken	rough handling	-	No trip	measurement of coilresistance	handle with care	2	3	5	**30**
Actuation	Drag magnet		drag disc										
	29	Locking nut	adjust drag on disk	loose	not tightened in last adjustment	-	Conditional: no effect if magnetposition still fixed	Setting / calibration	tighten nut	3	1	5	**15**
	30	Locking nut		stuck	corrosion	no longer adjustable	Conditional: no effect if adjusted ok	Setting / calibration	none	3	1	1	**3**
	31	Magnet	cause drag on disk	decreased magnetic strength	magnetic material degradation	possible less drag	Early trip	Adjustment of drag (no adjustment tolerance)	none	5	1	3	**15**
	32	Magnet		damaged / broken	rough handling	possible less drag	Early trip	Visual inspection	handle with care	3	2	3	**18**

Induction disc relay GE IFC serie **Failure mode effects and criticality analysis**

	Subsystem	**System element**	**Function**	**Failure mode**	**Failure causes**	**Failure effect Local effect**	**End effect**	**Failure detection**	**Preventive actions**	**Detection D**	**Occurrence O**	**Severity S**	**RPN**
Tripping	Seal in unit		latch tripsignal										
	33	(su) Coil (tapped)	create emf	short circuit	aged insulation		No seal-in	measure resistance	none	2	3	5	**30**
	34	(su) Coil (tapped)		short circuit	dirt/dust		No seal-in		none	2	3	5	**30**
	35	(su) Coil (tapped)		broken	rough handling		No seal-in	measure resistance	handle with care	2	3	5	**30**
	36	(su) Coil (tapped)		loose	disconnected		No seal-in	measure resistance	check connections after disconnection	2	2	5	**20**
	37	(su) Armature	actuate contact movement	stuck	dirt/dust	no closing of contacts	No seal-in	Functional test	none	2	2	5	**20**
	38	(su) Taps	set magnitude of detection current	no detection	wrongly set	-	No seal-in	functional test	compare with tapsetting main unit	2	2	5	**20**
	39	(su) Taps		loose	disconnected	-	No seal-in	Check connections	check connections after disconnection	2	2	5	**20**
	40	(su) contacts	close tripcircuit	No electrical contact	dirt/dust	contacts don't close electrically	No trip	measure contact resistance	check contacts	2	3	5	**30**
	41	(su) contacts		No electrical contact	wrongly set	contacts don't close electrically	No trip	measure contact resistance	check contacts	2	3	5	**30**
	42	(su) contacts		bad electrical contact	dirt/dust	contact chatter	Delayed trip	measure contact resistance	check contacts	2	3	4	**24**
Tripping	Stationary contact & zero timedial		Support stationary contact and end travel of disc										
	43	Upper stationary contact	make electrical contact	No electrical contact	dirt/dust	contacts don't close electrically	No trip	measure contact resistance	clean/polish contact	2	3	5	**30**
	44	Upper stationary contact		No electrical contact	wrongly set	contacts don't close electrically	No trip	measure contact resistance	clean/polish contact	2	3	5	**30**
	45	Upper stationary contact		bad electrical contact	dirt/dust	contact chatter	Delayed trip	measure contact resistance	clean/polish contact	2	3	4	**24**
	46	Stationary contact adjusting screw	adjust contact position	loose	wrongly set	contact chatter	Delayed trip	setting/calibration	tighten after adjustment	3	1	3	**9**
	47	Stationary contact adjusting screw		damaged	rough handling	Contact distance no longer adjustable	Conditional: no effect if adjustment is ok	setting/calibration	handle with care	3	1	4	**12**
	48	Stationary contact adjusting screw		stuck	corrosion	Contact distance no longer adjustable	Conditional: no effect if adjustment ok	setting/calibration	handle with care	3	1	1	**3**
	49	Lower stationary contact	make electrical contact	No electrical contact	dirt/dust	contacts don't close electrically	No trip	measure contact resistance	clean/polish contact	2	3	5	**30**
	50	Lower stationary contact		No electrical contact	wrongly set	contacts don't close electrically	No trip	measure contact resistance	clean/polish contact	2	3	5	**30**
	51	Lower stationary contact		bad electrical contact	dirt/dust	contact chatter	Delayed trip	measure contact resistance	clean/polish contact	2	3	4	**24**
	52	Moving contact	make electrical contact	No electrical contact	dirt/dust	contacts don't close electrically	No trip	measure contact resistance	clean/polish contact	2	3	5	**30**
	53	Moving contact		No electrical contact	wrongly set	contacts don't close electrically	No trip	measure contact resistance	clean/polish contact	2	3	5	**30**
	54	Moving contact		bad electrical contact	dirt/dust	contact chatter	Delayed trip	measure contact res	clean/polish contact	2	3	5	**30**

Detection input sheets

failure detection time setting & calibration

	Disc stop arm				**Disc centering & end play**										**Time dial**			
	bronze leaf spring			**clampig screws**	**Upper pivot**			**upper pivot adjusting screw**	**jewel screw**			**jewel screw set screw**			**time dial lock screws**		**spring / wave washer**	
	broken spring	Wrongly set	bent spring	loose	loose	damaged	stuck	loose	poor disk in gap alignment	damaged	stuck	loose	stuck	damaged	broken	loose	broken	stuck
Absolute uncertainty																		
Remote	**4**		**4**		**4**	**4**	**4**	**4**	**4**								**4**	**4**
Low		**3**		**3**						**3**	**3**	**3**	**3**	**3**				
High															**2**	**2**		
Almost certain																		

Rank	
Absolute uncertainty	*5*
Remote	*4*
Low	*3*
High	*2*
Certain	*1*

Failure detection U magnet

	U-magnet							
	coil (upper pole)			**taps**		**coil (lower pole)**		
	shorted	loose	broken	wrong tap /no detection	loose	shorted	loose	broken
Absolute uncertainty								
Remote								
Low				**3**				
High	**2**	**2**	**2**		**2**	**2**	**2**	**2**
Almost certain								

Rank	
Absolute uncertainty	5
Remote	4
Low	3
High	2
Certain	1

Failure detection actuation

	Drag magnet			
	locking nut		**magnet**	
	loose	stuck	decreased magnetic strength	damaged/broken
Absolute uncertainty			**5**	
Remote				
Low	**3**	**3**		**3**
High				
Almost certain				

Rank	
Absolute uncertainty	5
Remote	4
Low	3
High	2
Certain	1

Failure detection tripping

	Seal in unit								**Stationary contact & zero timedial**								
	(s.u.) coil, tapped			**(s.u.) armature**	**(s.u.) taps**		**(s.u.) contacts**		**upper stationary contact**		**stationary contact adjusting screw**			**lower stationary contact**		**Movable contact**	
	shorted	broken	loose	stuck	wrong tap /no detection	loose	no electrical contact	bad electrical contact	no electrical contact	bad electrical contact	loose	damaged	stuck	no electrical contact	bad electrical contact	no electrical contact	bad electrical contact
Absolute uncertain																	
Remote																	
Low											**3**	**3**	**3**				
High	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**				**2**	**2**	**2**	**2**
Almost certain																	

Rank	
Absolute uncertainty	5
Remote	4
Low	3
High	2
Certain	1

Severity input sheets

	Disc stop arm				Disc centering & end play										Time dial			
system element	**bronze leaf spring**			**clampig screws**	**Upper pivot**			**upper pivot adjusting screw**	**jewel screw**			**jewel screw set screw**			**time dial lock screws**		**spring / wave washer**	
cause	broken spring	Wrongly set	bent spring	loose	loose	damaged	stuck	loose	poor disk in gap alignment	damaged	stuck	loose	stuck	damaged	damaged	loose	broken	stuck
catastrophic	**5**																**5**	**5**
critical				**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**			**4**	**4**	**4**		
moderate		**3**	**3**									**3**						
marginal																		
minor													**1**					

Rank	
catastrophic	*5*
critical	*4*
moderate	*3*
marginal	*2*
minor	*1*

Severity detection

	U-magnet							
	coil (upper pole)			**taps**		**coil (lower pole)**		
	shorted	loose	broken	wrong tap /no detection	loose	shorted	loose (wiring)	broken (wiring)
catastrophic	**5**		**5**	**5**	**5**	**5**	**5**	**5**
critical		**4**						
moderate								
marginal								
minor								

Rank

catastrophic	*5*
critical	*4*
moderate	*3*
marginal	*2*
minor	*1*

	Drag magnet			
	locking nut		**magnet**	
	loose	stuck	decreased magnetic strength	damaged/broken
catastrophic	**5**			
critical				
moderate			**3**	**3**
marginal				
minor		**1**		

Rank	
catastrophic	*5*
critical	*4*
moderate	*3*
marginal	*2*
minor	*1*

	Seal in unit								**Stationary contact & zero timedial**							**Movable contact**	
	(s.u.) coil, tapped			**(s.u.) armature**	**(s.u.) taps**		**(s.u.) contacts**		**upper stationary contact**		**stationary contact adjusting screw**			**lower stationary contact**			
	shorted	broken	loose	stuck	wrong tap /no detection	loose	no electrical contact	bad electrical contact	no electrical contact	bad electrical contact	loose	damaged	stuck	no electrical contact	bad electrical contact	no electrical contact	bad electrical contact
catastrophic	**5**	**5**	**5**	**5**	**5**	**5**	**5**		**5**					**5**		**5**	**5**
critical								**4**		**4**		**4**			**4**		
moderate											**3**						
marginal																	
minor													**1**				

Rank	
catastrophic	*5*
critical	*4*
moderate	*3*
marginal	*2*
minor	*1*

A3 Results of the FMECA procedure

List of components, failures and detection provisions

Table 17. component failures in time setting & calibration

Time setting & Calibration	**Failure**	**Detection provision**
Bronze leaf spring	Broken spring	Case open inspection / maintenance
	Wrongly set	Case open inspection / maintenance
	Bent	Case open inspection / maintenance
Clamping screws	Loose	Case open inspection / maintenance
Upper pivot	Loose	Case open inspection / maintenance
	Damaged	Case open inspection / maintenance
	Stuck	Case open inspection / maintenance
Upper pivot adjusting screw	Loose	Case open inspection / maintenance
Jewel Screw	Wrongly set	Case open inspection / maintenance
	Damaged	Case open inspection / maintenance
	Stuck	Case open inspection / maintenance
Jewel screw set screw	Loose	Case open inspection / maintenance
	Stuck	Case open inspection / maintenance
	Damaged	Case open inspection / maintenance
Time dial lock screw	Broken	Case open inspection / maintenance
	Loose	Case open inspection / maintenance
Spring/ wave washer	Broken	Case open inspection / maintenance

	Stuck	Case open inspection / maintenance

Table 18. Components and failures in detection

Detection		
	Failure	**Detection provision**
Coil (upper pole)	short circuit	Circuitry measurement
	Loose	Circuitry measurement
	Broken	Circuitry measurement
Taps	Loose	Visual inspection, tightening screws / pulling wire connections
	No detection	Visual inspection, tightening screws / pulling wire connections
Coil (lower pole)	Loose	Circuitry measurement
	Broken	Circuitry measurement
	Short circuit	Circuitry measurement

Table 19. Components and failures in actuation

Actuation		
	Failure	**Detection provision**
Locking nut	Loose	Case open inspection / maintenance
	Stuck	Case open inspection / maintenance
Magnet	Decreased magnetic strength	
	Damaged/broken	Case open inspection / maintenance

Table 20. components and failures in tripping

Tripping	**Failure**	**Detection provision**
(seal in unit) Coil (tapped)	Short circuit	Circuitry measurement
	Broken	Circuitry measurement
	Loose	Circuitry measurement
(seal in unit) Armature	Stuck	Functional test
(seal in unit) Taps	Loose	Circuitry measurement
	No detection	Circuitry measurement
	No electrical contact	Circuitry measurement
	Bad electrical contact	Circuitry measurement
Stationary contact adjusting screw	Loose	Case open inspection / maintenance
	Damaged	Case open inspection / maintenance
	Stuck	Case open inspection / maintenance
Upper stationary contact	No electrical contact	Circuitry measurement
	Bad electrical contact	Circuitry measurement
Lower stationary contact	No electrical contact	Circuitry measurement
	Bad electrical contact	Circuitry measurement
Moving contact	No electrical contact	Circuitry measurement
	Bad electrical contact	Circuitry measurement

RPN tables for calculation of RPN_w

	Induction disc relay GE IFC series		Failure mode effects and criticality analysis							
	Subsystem	System element	Function	Failure mode	Detection D	Occurrence O	Severity S	RPN		
time setting & calibration	Disc stop arm		facilitate stationary contact and end disc travel							
	1	bronze leaf spring	prevent sticking of stop arm to time dial stop	no actuation	4	2	5	**40**		
	2	bronze leaf spring		slow actuation	3	2	3	**18**		
	3	bronze leaf spring		no actuation	4	2	3	**24**		
	4	Clamping screws	clamp arm and leaf spring	no actuation	3	2	4	**24**		
time setting & calibration	Disc centering & end play		Alignment of disk in gap							
	5	Upper pivot	set end play, max. upper position	loose	4	1	4	**16**		
	6	Upper pivot		damaged	4	1	4	**16**		
	7	Upper pivot		stuck	4	1	4	**16**		
	8	Upper pivot adjusting screw	fixate upper pivot	loose	4	1	4	**16**		
	9	Jewel screw	support disk in gap	poor disk in gap alignment	4	1	4	**16**		
	10	Jewel screw		damaged	3	1	4	**12**		
	11	Jewel screw		stuck	3	1	4	**12**		
	12	Jewel screw set screw	fixate jewel screw	loose	3	1	3	**9**		
	13	Jewel screw set screw		stuck	3	1	1	**3**		
	14	Jewel screw set screw		damaged	3	1	4	**12**		
time setting & calibration	Time dial		set time delay							
	15	Time dial lock screws	fix position time dial to prevent backtravel due to reversed torque	broken	2	1	4	**8**		
	16	Time dial lock screws		loose	2	1	4	**8**		
	17	Spring/wave washer	A flat spring designed to provide a compression force eliminate take up tolerance and rattle	broken	4	1	5	**20**	Sum	RPNw
	18	Spring/wave washer		stuck	4	1	4	**16**	286	**13**

Detection	U-magnet			create emf in coils		D	O	S	RPN		
		19	Coil (upper pole)	create/induce emf in disc	short circuit	2	3	5	**30**		
		20	Coil (upper pole)		short circuit	2	3	5	**30**		
		21	Coil (upper pole)		loose	2	4	4	**32**		
		22	Coil (upper pole)		broken	2	4	5	**40**		
		23	Taps	set magnitude of detection current	no detection	3	2	5	**30**		
		24	Taps		loose	2	2	5	**20**		
		25	Coil(lower pole)	create/induce emf in disc	short circuit	2	3	5	**30**		
		26	Coil(lower pole)		short circuit	2	3	5	**30**		
		27	Coil(lower pole)		loose	2	3	5	**30**	Sum	RPNw
		28	Coil(lower pole)		broken	2	3	5	**30**	302	**24**
Actuation	Drag magnet			drag disc		D	O	S	RPN		
		29	Locking nut	adjust drag on disk	loose	3	1	5	**15**		
		30	Locking nut		stuck	3	1	1	**3**		
		31	Magnet	cause drag on disk	decreased magnetic strength	5	1	0	**0**	Sum	RPNw
		32	Magnet		damaged / broken	3	2	3	**18**	36	**7**

Tripping	Seal in unit			latch tripsignal		D	O	S	RPN
		33	(su) Coil (tapped)	create emf	short circuit	2	3	5	**30**
		34	(su) Coil (tapped)		short circuit	2	3	5	**30**
		35	(su) Coil (tapped)		broken	2	3	5	**30**
		36	(su) Coil (tapped)		loose	2	2	5	**20**
		37	(su) Armature	actuate contact movement	stuck	2	2	5	**20**
		38	(su) Taps	set magnitude of detection current	no detection	2	2	5	**20**
		39	(su) Taps		loose	2	2	5	**20**
		40	(su) contacts	close tripcircuit	No electrical contact	2	3	5	**30**
		41	(su) contacts		No electrical contact	2	3	5	**30**
		42	(su) contacts		bad electrical contact	2	3	4	**24**
Tripping	Stationary contact & zero timedial			Support stationary contact and end travel of disc					
		43	Upper stationary contact	make electrical contact	No electrical contact	2	3	5	**30**
		44	Upper stationary contact		No electrical contact	2	3	5	**30**
		45	Upper stationary contact		bad electrical contact	2	3	4	**24**
		46	Stationary contact adjusting screw	adjust contact position	loose	3	1	3	**9**
		47	Stationary contact adjusting screw		damaged	3	1	4	**12**
		48	Stationary contact adjusting screw		stuck	3	1	1	**3**
		49	Lower statonary contact	make electrical contact	No electrical contact	2	3	5	**30**
		50	Lower statonary contact		No electrical contact	2	3	5	**30**
		51	Lower statonary contact		bad electrical contact	2	3	4	**24**
		52	Moving contact	make electrical contact	No electrical contact	2	3	5	**30**
		53	Moving contact		No electrical contact	2	3	5	**30**
		54	Moving contact		bad electrical contact	2	3	5	**30**

Sum	RPNw
536	**19**

Tables for calculation of Criticality

Component numbers											
sticking/no actuation	1	2	3	4							
decreased magnetic strength	31										
Loose	5	8	12	16	21	24	27	29	36	39	46
Damaged/broken	6	10	14	15	17	22	28	32	35	47	
Stuck	7	11	13	18	30	37	48				
Poor disk aligment	9										
Short circuit	19	20	25	26	33	34					
No detection	23	38									
bad electrical contact	42	45	51	54							
No electrical contact	40	41	43	44	49	50	52	53			

occurrence of failure mode												Ofm		Ofm	Sfm		Cfm
sticking/no actuation	2	2	2	2								2,0	8	2	4	{1}	8
decreased magnetic strength	1											1,0	3	1	3	{2}	3
Loose	1	1	1	1	4	2	3	1	2	2	1	1,7	7,707	2	4	{3}	8
Damaged/broken	1	1	1	1	1	4	3	2	3	1		1,8	8,14	2	4	{4}	8
Stuck	1	1	1	1	1	2	1					1,1	3,324	1	3	{5}	3
Poor disk aligment	1											1,0	4	1	4	{6}	4
Short circuit	3	3	3	3	3	3						3,0	15	3	5	{7}	15
No detection	2	2										2,0	10	2	5	{8}	10
bad electrical contact	3	3	3	3								3,0	12,94	3	4	{9}	13
No electrical contact	3	3	3	3	3	3	3	3				3,0	15	3	5	{10}	15

severity of failure mode												Sfm
sticking/no actuation	5	3	3	4								3,8
decreased magnetic strength	3											3,0
Loose	4	4	3	4	4	5	5	5	5	5	3	4,3
Damaged/broken	4	4	4	4	5	5	5	3	5	4		4,3
Stuck	4	4	1	5	1	5	1					3,0
Poor disk aligment	4											4,0
Short circuit	5	5	5	5	5	5						5,0
No detection	5	5										5,0
bad electrical contact	4	4	4	5								4,3
No electrical contact	5	5	5	5	5	5	5	5				5,0

A4 Input tables for observations and efforts

Adjustment of time settings		
Adjusted? Yes (1) / No (9)	not adjusted	0
	Yes	1
	No	9
Inputcircuit measurement		
	Not carried out	0
	Yes	1
	No	9
Outputcircuit measurement		
	not carried out	0
	Yes	1
	No	9
Wye point measurement		
	not carried out	0
	Yes	1
	No	9
Tightening terminal screws		
	not carried out	0
	Yes	1
	No	9
Cleaning contacts		
	not carried out	0
	necesarry	1
	not necesarry	9

Pickup function (only with induction types)		
functional?	Not conducted	0
	functional	1
	not functional	9
Seal-in function		
functional?	Not conducted	0
	functional	1
	not functional	9
Indication (flag)		
	Not conducted	0
	functional	1
	not functional	9
Trip circuit test		
	Not conducted	0
	functional	1
	not functional	9
CB operates on trip yes (9) / no (1)		
	Not conducted	0
	functional	1
	not functional	9
Terminal check		
CT disconnected	not checked	0
	Yes	1
	No	9
Loose Lead(s)		
	not checked	0
	Yes	1
	No	9
Power supply disconnected		
	not checked	0
	Yes	1
	No	9
Contactfunction		
	not checked	0
	bad	1
	Good	9
Drop-out time meeting requirements		
	not checked	0
	Yes	1
	No	9

A5 Test report

Manufacturers test report

Over current protection

Test protocol					**MS 810 P1/**	11,78		
Client:	Raszig Gmbh, Pforzheim							
Installation:	Papermill							
Installationsection/id nr.:	Pulp sieve						**Feeder :**	BA3
Setting Ranges	2.5MVA-trafo, 6/0.4kV,Uk=6%, Jn=240/3620 A							
CT ratio	250/1A	5P10	**Core**	15 VA			**Earthed side:**	R1
Voltage	at 6kV							
Type:	GE IFC 51		**group:**	-			**Manufact. No:**	X8-10
Mount type	draw out						**Aux. Voltage:**	220 V, -Hz
Settings	**J> L1, L2,L3**		**J> L1, L2,L3**	**Je**	**t>**	**t>>**		
	1.8 to 3.6 A		6 to 20 A	- to - A	0.1 to 8s	0.1 to 8s		

Pick up test conducted with: Secondary testeqt SRP4 and timing unit B2040

	J> (A)			**J>> (A)**			**Je**	**t> (s)**	**t>> (s)**
Settings	2.7A **2.** 675A			8A **2.** 2000A			- **2.** - A	1 **s**	0.5 **s**
Phase	**L1**	**L2**	**L3**	**L1**	**L2**	**L3**	**L1, L2,L3**	**L1, L2,L3**	**L1, L2,L3**
Pick up	2.75	2.7	2.75	8.5	8.5	8.5	-	1	0.5
Drop out	2.35	2.20	2.30	-	-	-	-	-	-

Check of clearance and signalling: Circuitbreaker 6 kV and 400V; over current 2,5 MVA-transformer

Remarks: Complete documentation of Voltage protection was available

i. A. Heinz (ZN-Stgt. MA)	N. Redlich (E-Commisioning)
Supplier	**Commissioning engineer**
HEINZ	REDLICH
Name	**Name**

Location Pforzheim

Date 3.5.78

(by courtesy of Siemens)

Proposed test report

Substation	Noord Papaverweg	**Created on**	25-12-05
Location code	NDP	**Ordered by**	PowerC/maintenance
Region	Amsterdam / Gooi	**Networkcode**	
Feeder nr	112	**Engineer**	John Doe
Address	Papaverweg 55	**Supervised by**	Pete Doe
Location	Amsterdam 1032 KJ	**Carried out on**	25-12-2005
Voltage	10 kV	**Kind of insp.**	Combi 10kV (Funct + Inspect.)

Test form

Function	IIIMa+T
Manufacturer	Siemens
Type	R3As7

Result of inspection 6

Functional(9) /Functional (exchange if possible) (6) / Exchange (1)

9	6	1

Test eqt. GE-Freya

Settings

Pickup current

Overcurrent		**Short circuit**	
I >		**I >>**	
2,7	A	8	A

Pick up time

T1 >		**T1 >>**	
1	s	0,5	s

Measurements

As found Zero check

Pick up current

Timing test		Instantaneous	
Overcurrent		**Short circuit**	
I >		**I >>**	
2,7	A	8	A
Pick up time			
T1 >		**T1 >>**	
1	s	0,5	s
Drop out time			
T2 >		**T2 >>**	
0,8	s	0,8	s

Measurements

Left (change in case of adjustment)

Pick up current

Timing test		Instantaneous	
Overcurrent		**Short circuit**	
I >		**I >>**	
2,7	A	8	A
Pick up time			
T1 >		**T1 >>**	
1	s	0,5	s
Drop out time			
T2 >		**T2 >>**	
0,8	s	0,8	s

Observations

(Change inputs only if appplicable)

Pickup function (only with induction types)	
Functional (9) / not functional (1)	0
Seal-in function	
Functional (9) / not functional (1)	9
Indication (flag)	
Functional (9) / not functional (1)	9
Trip circuit test	
CB operates on trip yes (9) / no (1)	9
Terminal check	
CT/ PT disconnected	
Yes (9) / No (1)	0
Loose Lead(s)	
Yes (9) / No (1)	0
Power supply disconnected	
Yes (9) / No (1)	0
Contactfunction	
Good (9) / Bad (1)	9
Drop-out time meeting requirements	
Yes (9) / No (1)	1

Efforts

Adjustment of time settings	
Adjusted? Yes (1) / No (9)	9
Inputcircuit measurement	
Ok? Yes (9) / No (1)	0
Outputcircuit measurement	
Ok? Yes (9) / No (1)	0
Wye point measurement	
Ok? Yes (9) / No (1)	1
Tightening terminal screws	
Carried out? Yes (1) / No (9)	1
Cleaning contacts	
Necesarry? Yes (1) / No (9)	9

Remarks (Observations/Efforts different than mentioned)

Coding explanation: (0) not carried out/observed (1) "comment" (9) "comment"

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