Risk-based maintenance and replacement strategy for protection relays
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Network operators do have several generations of protection relays in operation, ranging from the old electromechanical relays, which can be up to 60 years old, till new digital relays. Important questions are how these relays should be maintained, and when the old relays have to be replaced for new ones. When this is done too late, malfunctioning of the relays might result in false or a-selective tripping, posing a threat to network reliability. On the other hand network operators want to run their network in the most cost-effective way. This will cause, amongst others, that network operators want to keep protection relays (and other equipment) in operation as long as possible. This might cause an increase in maintenance costs however. Therefore network operators have to find an optimal balance between network reliability, maintenance costs and the costs of replacement.

1 Various steps in the RBAM-process

- **Risk identification and analysis**
- **Development several investment alternatives**
- **Approval**
- **Program Management**
- **Feedback**
Enexis, one of the largest distribution network operators in The Netherlands uses its Risk-Based Asset Management (RBAM) approach to find an optimal long-term maintenance and replacement strategy for its protection relays. In this process the optimum has been found between the costs for maintenance or replacement on one side, and the risk on false or a-selective tripping on the other side.

The result is a long-term replacement and maintenance strategy for all the types and generations of protection relays that are used in the network. As an example it is presented how the maintenance and replacement strategy is determined for electromechanical distance relays in a medium-voltage (MV) transmission network. A MV transmission network is a N-1 redundant network, as shown in Figure 2.

In case of an outage of one of the cables, the other cable(s) have enough capacity to still supply the load. In order to have selective clearing of a fault, these networks are protected by either distance or differential relays.

The article starts with a general part, describing the way in which inspection and maintenance of relays is performed within Enexis and with a short description of the Risk-Based Asset Management (RBAM) approach. In the next part this is, as an example, applied to one specific group of relays: electromechanical distance relays. It will first be investigated which are the dominant failure causes of electromechanical distance relays and how often they occur. Further it will be investigated how large the risk is of false or a-selective tripping when no (additional) maintenance is done, or when relays will not be replaced. And it will be identified what are the costs for keeping the relays in operation versus the costs of replacement of the relays.

Based on these inputs it will be described how the long-term maintenance and replacement strategy is developed.

**Inspection and Maintenance of Protection Relays**

Inspection and maintenance of the electromechanical protection relays is done every year or once per three year. The frequency is dependent on the average state of the population of that type of relay and on the location in the network. Those relays that will result in disconnection of larger areas when they fail, are inspected more often than relays which only will cause disconnection of a small area.

In order to determine which inspections and what kind of maintenance has to be done for each type of relay, a document is made (a so-called ‘component quality document’), that describes the main fail mechanisms of that type of relay. There are two main sources that give input to these documents. The first is the experience from the protection specialists. The second are the so-called fail-codes. For each type of failure a so-called fail-code is made. This describes the specific type of failure. The next time the same type of failure is observed, the same fail code will be used. In this way also statistical data is obtained of how often certain fail codes occur.

For each fail code, describing a certain fail mechanism, it is determined whether or not it can be solved (and whether that is economically feasible). When it can be solved, it is also prescribed how that can be done.

Some fail codes describe situation in which the relays doesn’t function at all. Most fail codes are related to deviations in the settings however. In case of deviations, it is also important to determine the maximum deviations that are allowed. These maximum deviations are defined as the so-called ‘disapproval criteria’.

These disapproval criteria are directly related to the protection philosophy that is applied. To give an example: in the protection philosophy it is assumed that certain settings of the relay have a margin of maximum 5%. This means...
The chance that as long the deviations of the relay settings are below 5% no a-selectivity will occur. But this also means that when during testing the settings show a deviation of more than 5%, the relay setting should be adjusted again or the relay should be replaced. Which of the two is chosen depends on several things, such as the ‘quality’ of the relay and the setting (how fast will it deviate again), the expected remaining lifetime of the relay, the costs of adjusting or repairing, etc.

Also here the maximum deviations that are allowed depend on the location of the relay in the network. Relays that give a small interruption in case of false operation are allowed to have larger deviations, than relays that can result in a large-scale disconnection.

When the interval in which relays fail (either complete failure, or deviation of settings), it is a certain moment better and more cost-effective to replace the whole population of this type of relay. To determine the best solution (increasing inspection frequency or replacement of the whole population) the Risk-Based Asset Management (RBAM) methodology is used, as described in chapter 3. The input for these analyses are the component quality documents and the fail codes (especially the fail rate of the components). When in the future the certain fail rates increase, the analyses can easily be repeated, and in this way the best moment can be determined for replacement of the complete population of a certain type of relay.

**Risk-Based Asset Management (RBAM)**

The methodology that is applied is based on the Risk Based Asset Management (RBAM) approach developed by Enexis. This approach has been certified against the well-known international PAS-55 and ISO 9001: 2000 standards since 2006.

In the RBAM-process, as depicted in Figure 1, the Asset Manager’s task is to identify and analyse risks that threaten the business-values of the Asset Owner. In the next step, the Asset Manager formulates different strategies in order to reduce these risks. Strategies with the highest expected yield, in terms of risk reduction per Euro spent, are selected to be implemented. After implementation, the effectiveness and efficiency of the chosen strategies are evaluated.

For the risk analysis, a so-called ‘risk matrix’ is used. With the help of this matrix, the impact of a certain risk on the company values of Enexis can be determined. The company values of Enexis are: Reliability, Safety, Legal, Economy, Customer satisfaction and Sustainability.

The risk-matrix contains 6 risk levels: Negligible, Low, Medium, High, Very High and Unacceptable. Each risk level is determined by the product of the frequency of its occurrence on the one hand and its effect on the other hand.

**Inspection and Maintenance of Electromechanical Distance Relays**

As described for each type of relay so-called component quality documents are made in which the main fail mechanisms are described, and how they can be repaired. In this section a short description is given of the main fail mechanisms of electromechanical distance relays are given, as well how they can be solved.

**Relay does not switch due to pollution:** Due to pollution, several contacts in the relay can have a high contact resistance, with the risk that the relay will not work at all, or will have a delay. The solution in this case is cleaning the contacts, or when the pollution is too high, replacing the relay.

**Backward fault is switched off immediately:** In the relay springs are used. The force that is exerted by the spring can reduce when it becomes older. When the force is too low, the relay will switch off immediately in case of a backward fault. The solution in this case is replacing the spring by a new one, or replacing the complete relay.

**Time setting is drifting:** Over time the time setting can become different from what is shown on the time scale of the relay. This can result in a too fast or a too slow operation of the relay. The solution in this case is adjusting the time scale, or when the fault is to large, replacing the relay.

**Relay contact is booming (continuous opening and closing at high frequency):** When the contact pressure of the switch-off contact is too low, the contact will be booming. This will continuously interrupt the current in the switch-off coil, resulting in a longer time before the circuit breaker opens. The solution in this case is to adjust the pressure setting if possible, or otherwise replace the relay.

**Distance relays SD14 & SD34**

The protection relays in MV transmission networks protect the MV transmission cables and the MV/MV substations.
Table 1: Resulting risk levels per company value

<table>
<thead>
<tr>
<th>Type of Failure</th>
<th>Company value</th>
<th>Effect</th>
<th>Frequency</th>
<th>Risk level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviation of settings of distance relays</td>
<td>Economy</td>
<td>Considerable</td>
<td>Unlikely</td>
<td>Negligible</td>
</tr>
<tr>
<td></td>
<td>Reliability</td>
<td>Considerable</td>
<td>Yearly</td>
<td>High</td>
</tr>
</tbody>
</table>

**General Description of the Risk**

The risk that is considered in this paper is the malfunctioning of electromechanical protection relays in Medium Voltage (MV) transmission networks. Malfunctioning in this case is defined as ‘the incorrect functioning of the relay due to a defect / deviation in the relay’. Incorrect functioning due to reasons that cannot be related to the condition of the relay itself, such as incorrect settings or a wiring error, are not considered. Several failure mechanisms that can result in the malfunctioning are described in the previous chapter.

In general there are 3 different ways in which a protection relay can show incorrect operation:

- **Spontaneous trip:** although no short-circuit occurred the relay gives for some reason a spontaneous trip command. Depending on the redundancy in the network, this can result in an interruption of supply.

- **Incorrectly no trip (‘denial’):** during a short-circuit, the relay responsible to switch off that fault (main protection) gives no trip command. The back-up protection has to act, mostly resulting in a larger area that is interrupted. A delayed trip can also cause more damage to network components.

- **False trip (a-selective switch-off):** during a short-circuit the relay which should act as backup protection does not wait for the main protection but gives a premature trip command. From these three points it can be seen that failing of a protection relay has the largest impact on the company values ‘Reliability’ (due to interruptions in supply) and ‘Economy’ (due to damage to network components). On the other company values there is (almost) no influence.

**Risk Level**

**Effect of Failure:** The protection relays in MV transmission networks protect the MV transmission cables and the MV/MV substations. Splitting it up in the 3 previously mentioned ways of malfunctioning of a protection relay:

1) In case of a spontaneous trip by a relay in the MV transmission network normally only the transport cable will be switched off. Due to the N-1 redundancy no interruption of supply will occur. Therefore there will be no interruption of supply or damage in this case.

2) In a case where incorrectly no trip is given either the whole MV transmission network or the HV/MV transformer will be switched off. To the N-1 redundancy no interruption of supply will occur. Therefore there will be no interruption of supply or damage in this case.

3) In case of a-selective switch-off of a relay in the MV transmission network normally only a transmission cable will be switched off. Next the main protection of the distribution cable in which the fault occurred can still switch-off the fault correctly. Due to the N-1 redundancy no interruption of supply will occur. It is also possible however that the fault is in another cable of the same transmission network, resulting in switching off two cables instead of one. This can result in interruption in supply, but the chance that this will occur is small however.

**Chance on Failure**

**A. General:** The chance on failure of an individual relay depends on the condition or aging of this specific relay. As the population of electromechanical relays considered here is homogeneous in age and in environmental conditions, it can be stated that the condition/aging of these relays is quite similar. Therefore it can be assumed that the chance on failure is more or less the same for each individual relay in the population.

As is mentioned in the previous section only the risk on incorrectly not tripping of a relay is relevant. This can result in disconnection of a large(s) area or more damage to the switchgear in a MV/MV substation. To determine the chance that this will happen, in the first place the chance on failing of the relay itself is relevant. But, as long as there is no fault in the network that has to be switched off, there is no large(s) outage or damage. Therefore additionally it is necessary to determine the chance that during the time that the relay is defective, a fault in the network will occur. When the failure of the relay is detected in time, for example during periodic maintenance, and the relay is then repaired or replaced, there will be no problem. The chance that a latent relay defect will result in an actual failure is called ‘manifesting chance’.

**B. Manifesting chance:** The manifesting chance can be determined as follows:

- The average length of a transmission cable is about 5 km, with a failure rate of 0.0017 per km / per year. The change on a fault is therefore 0.085 per km. The failure rate of a MV/MV substation is very low and will not be taken into account.

- Periodic maintenance is carried out every 3 years (MV/MV substation) and once a year (HV/MV substation), thus on average a relay can have a defect for 1.5 or 0.5 years before it is detected. When in this period a fault will occur, it will result in failure of the protection and discon-
The chance for failure of an individual relay depends on the condition, or aging of this specific relay. The chance for failure can be calibrated again in case of small deviations, or otherwise it will be replaced. From tests that have been done it can be concluded that in 95% of the cases it was possible to calibrate the relay again, and 5% of the relays had to be replaced.

An important question is however how long a calibration lasts before a new calibration is required. This recurring deviation of relay settings is the reason for the current high inspection frequency (annual) in H/MV substations.

As the number of defect or incorrectly functioning relays is expected to increase in the future, this will result in more interruptions of supply. Also the expenditures for maintenance and replacement will increase. Because of the uncertainty in the increase of the failure rate a sensitivity analysis will be done, when calculating the yield of the possible solutions.

For the distance relays it is assumed that the failure rate of the relays will increase with 0.5% every year (so 3% 3.5% 4%, etc.). It will also become more difficult to repair the relays. Therefore it is assumed that the percentage of the relays that can be repaired will decrease with 5% every year (so 95% 90% 85%, etc.). With these assumptions it will take about 30 to 40 years before the complete population will have been replaced.

Higher frequency of inspection: The current practice of periodic inspection and condition based maintenance or replacement, can be continued with a higher frequency of inspection.

The inspection frequency in the MV/MV substations can be increased to once per year. This will give the same frequency as in the HV/MV substations. A higher inspection frequency will reduce the risk of failure of a relay, but it will also give higher costs. An even higher inspection frequency will give too much workload and is not considered to be realistic.

### Table 2: Calculations of investment cost v/s risk reduction

<table>
<thead>
<tr>
<th>Yield</th>
<th>Strategy 1</th>
<th>Strategy 2</th>
<th>Strategy 3</th>
<th>Strategy 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPV 50 years</td>
<td>Continue current policy</td>
<td>Higher frequency of inspection</td>
<td>Lower frequency of inspection</td>
<td>Preventive replacement</td>
</tr>
<tr>
<td>Reliability</td>
<td>€25,879,275</td>
<td>€18,546,814</td>
<td>€55,209,121</td>
<td>€4,197,786</td>
</tr>
<tr>
<td>Safety</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
</tr>
<tr>
<td>Legal</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
</tr>
<tr>
<td>Economy</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
</tr>
<tr>
<td>Customer Satisfaction</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
</tr>
<tr>
<td>Sustainability</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
<td>€------</td>
</tr>
<tr>
<td>Total</td>
<td>€25,879,275</td>
<td>€18,546,814</td>
<td>€55,209,121</td>
<td>€4,197,786</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Investment and costs</th>
<th>Strategy 1</th>
<th>Strategy 2</th>
<th>Strategy 3</th>
<th>Strategy 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV 50 years</td>
<td>Continue current policy</td>
<td>Higher frequency of inspection</td>
<td>Lower frequency of inspection</td>
<td>Preventive replacement</td>
</tr>
<tr>
<td>Total</td>
<td>€6,898,976</td>
<td>€7,991,744</td>
<td>€10,471,448</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Result</th>
<th>Strategy 1</th>
<th>Strategy 2</th>
<th>Strategy 3</th>
<th>Strategy 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>€32,420,413</td>
<td>€27,521,437</td>
<td>€63,200,865</td>
<td>€142,671,234</td>
</tr>
<tr>
<td>Savings</td>
<td>€6,898,976</td>
<td>€28,780,453</td>
<td>€19,749,178</td>
<td></td>
</tr>
</tbody>
</table>
Lower frequency of inspection: It is also possible to decrease the inspection frequency. In the HV/MV substations it could be reduced to 1x/3 year, the same as in the MV/MV substations. This will decrease the maintenance costs, but it will increase the risk of failure of a relay. A further reduction of inspection frequency is not realistic, because every three years the circuit breaker is tested and the testing of the relay can be combined.

Preventive replacement: By preventive replacement of the electromechanical relays the chance on a defective relay is reduced and therefore also the chance on failure of a relay. As the preventive replacement is carried out as a project, the cost for replacement will be lower than in case of single corrective replacements after a failure. Specifically for relays in the HV/MV substations the inspection frequency can be lowered from once per year to 1x/3 year, resulting in lower maintenance costs. In the calculation of investment cost versus risk reduction it is assumed that the new (digital) relay has to be replaced again after 20 years.

Strategy

Comparison of possible solutions: The next step is to investigate whether different solutions are profitable or not, and to compare them to each other. In order to determine whether the solutions are profitable, the risks that have been defined are expressed in euros. For the company value ‘Economy’ this is easy, as it is expressed in Euros already. Also the company value ‘Reliability’ can be expressed in euros however, as each Customer Minute Lost (CML) is representing a certain social cost to the society. With these costs it is possible to determine the total Net Present Value (NPV) of the risk reduction of a certain solution over a certain period. The NPV of this risk reduction can then be compared to the NPV of the required investments and it can be determined whether the solutions are profitable or not.

In Table 2 the results of the calculation of investment cost versus risk reduction are given. The assumptions behind these calculations have been given already in the previous sections. In order to check the robustness of the results, the calculation is repeated with the assumption that the failure rate will stay constant in the future (3%) and that also the maintainability will stay the same (95%) (Table 3).

In both cases strategy 2 (higher inspection frequency) and 4 (preventive replacement) are cost-effective, with the highest yield for strategy 2. When however the failure rate in the future will increase faster than previously assumed, strategy 4 will have the highest gain.

This development is quite likely, as the previous assumption that the relays will fail the coming 30 to 40 years is a conservative one, as the relays have a high average age already.

In addition to the quantitative approach, also some qualitative arguments can be mentioned:

- A more labor-extensive solution is favorable, given the expected shortage of technical personnel
- Future new employees have no knowledge of or affinity with the old electromechanical relays. They have more affinity with the modern digital technology

Strategy:

The sum of the qualitative and quantitative arguments results in the strategy of preventive replacement of the distance relays and the continuation of the current policy for the differential and directional overcurrent relays. The replacement of the distance relays will be spread out over a period of 5 years. The coming years the risk level due to the failure of the distance relays will gradually reduce to zero with the replacement of the relays.

Conclusion

Network operators need to have a long term maintenance and replacement strategy for protection relays. In this article it is presented how such a strategy can be developed, with the goal of finding the optimal balance between network reliability, maintenance costs and the costs for replacement. As an example the strategy is elaborated for electromechanical distance relays. In the same way also strategies have been developed for other types and generations of relays, giving a long-term maintenance and replacement strategy for all relays in the network of Enexis.

Table 3: Repeated calculations of investment cost v/s risk reduction with failure rate 3% and maintainability 95%

<table>
<thead>
<tr>
<th>Strategy</th>
<th>NPV 50 years</th>
<th>Investment and costs</th>
<th>Company values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continue current</td>
<td>€ 6.898.976</td>
<td>€ 6.898.976</td>
<td></td>
</tr>
<tr>
<td>policy</td>
<td>€ 7.991.744</td>
<td>€ 10.473.448</td>
<td></td>
</tr>
<tr>
<td>Higher frequency</td>
<td>€ 28.780.453</td>
<td>€ 14.671.234</td>
<td></td>
</tr>
<tr>
<td>of inspection</td>
<td>€ 25.879.275</td>
<td>€ 4.197.786</td>
<td></td>
</tr>
<tr>
<td>Lower frequency</td>
<td>€ 18.546.814</td>
<td>€ 55.209.121</td>
<td></td>
</tr>
<tr>
<td>of inspection</td>
<td>€ 25.879.275</td>
<td>€ 55.209.121</td>
<td></td>
</tr>
<tr>
<td>Preventive</td>
<td>€ 4.397.786</td>
<td>€ 4.397.786</td>
<td></td>
</tr>
<tr>
<td>replacement</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Reliability       | € 25.879.275 | € 18.546.814          | € 55.209.121   |
| Safety            | € 55.209.121 | € 4.397.786           | € 4.397.786    |
| Legal             | € 55.209.121 | € 4.397.786           | € 4.397.786    |
| Economy           | € 55.209.121 | € 4.397.786           | € 4.397.786    |
| Customer          | € 55.209.121 | € 4.397.786           | € 4.397.786    |
| Sustainability    | € 55.209.121 | € 4.397.786           | € 4.397.786    |
| Total             | € 25.879.275 | € 18.546.814          | € 55.209.121   |

Table 3: To check the robustness of the results, the calculation is repeated with the assumption that the failure rate will stay constant in the future (3%) and that also the maintainability will stay the same (95%).