CONDITION BASED MAINTENANCE ON MV CIRCUIT BREAKERS

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ABSTRACT
Condition based maintenance of MV circuit breakers represents an effective way to improve the continuity of supply, reducing operation costs as well. For this reason Enel Distribuzione, the major Italian utility in electric power distribution, has recently started a series of experimental analyses on this type of equipments, with the aim at finding out a way to implement a self-consistent diagnostic system. The application of a preliminary Failure Mode Effect Analysis allowed to determine the critical elements of circuit breaker, related to the most frequent failure modes experienced in service. Experimental tests, carried out on pre-defined quantitative failure configurations, provided interesting results for the selection of most significant diagnostic parameters and their respective sensor system. Cost Benefit Analysis lead the technical considerations and choices throughout this work.

INTRODUCTION
Electric companies in Europe have experienced important changes in the last decade, as a consequence of the electricity market liberalization. The increasing number of competitors made the major utilities reconsider their entire asset management, mainly for two order of reasons [2]:

- maximization of the return on investment by taking assets up to the end of their technical lifetime;
- minimization of service costs, maintaining at the same time a high level of reliability.

Electric utilities with a high number of installations face this task as a real challenge, because of the large amount of equipments and their variety (circuit breakers, transformers, electronic devices, etc., each one produced by different manufacturers).

In this scenario maintenance strategies play indeed an important role in order to improve progressively technical performances and economical savings.

Enel Distribuzione (ED), the major Italian utility in electric power distribution, has been recently reconsidering the whole maintenance policy of its electric installations, in accordance to the above mentioned reasons [3].

The first enhancement was obtained by ED through the standardization (ISO 9001:2000) of maintenance activities as well as addressing the asset management towards a Condition Based Maintenance (CBM), by means of new measurements in routine controls.

The stability of performance indicators, like the n° of failures, in the last two years, denotes a consolidated maintenance process but also highlights a narrow margin of improvement. One of the possibilities to gain a higher reliability is represented by predictive maintenance (the evolution of CBM), thus involving diagnostic tools for the classification of equipment state. The opportunities deriving from this approach could be:

- Optimization of interventions;
- Reduction of supply interruptions;
- Deeper knowledge of equipments’ behaviour.

ED has carried out a preliminary internal research in this field, focusing onto a specific type of MV switchgear, to assess the feasibility of industrial implementation of continuous monitoring of the equipment on service.

The target of this paper is to give an overview of the approach followed during the research, as summarized in the following steps:

1) analysis of HV/MV substations reliability and selection of the type of equipment to be studied;
2) application of Failure Mode Effect Analysis (FMEA) on the equipment selected;
3) design of experimental tests;
4) analysis of results and considerations on application.

EQUIPMENT SELECTION
Electric and electronic equipments in high voltage substations can be analysed in technical and economical terms, in order to estimate a ranking of their relevance. A preliminary study of these features was determinant for the identification of the assets on which focusing management optimization [2].

The following types of equipment were taken into account: Battery (Bat), Petersen coil (Pet), Power factor capacitor (Cap), Switchgear (SG), Relais (Rel), Rectifier (Rect), Overvoltage arrester (Arr), Disconnecting switch (Disc), Current transformer (CT), Voltage transformer (VT), Power transformer (PT), On load tap changer (OLTC).

Each component was evaluated on the basis of the following 4 factors:

- Occurrence of Failure
- Impact on Energy Delivery to final customer
- Mean time to repair
- Cost of corrective intervention

A scale of values from 1 to 5 (in ascending order of importance) was defined for each parameter. By multiplying the 4 factors and filtering only equipments with a final score (index of priority) higher than 18, the ranking so obtained is...
Figure 1. Index of priority of equipments installed in HV/MV substations

As data demonstrate, circuit breakers and power transformers represent the two components with the highest score. The decision to focus on circuit breakers, especially on MV class, was due to:

- the high number of these equipments (consequently their weight in the overall amount of interventions);
- the possibility to obtain a relatively prompt feedback from experimental applications;

The air-insulated switchgear selected for experimental tests (15 years on service) was respondent to the rated characteristics fixed by ED specifications (in accordance with IEC 62271-100) and common for all manufacturers:

- 24 kV operating voltage, 630 A continuous current, 50 Hz frequency, three-polar control, spring mechanism;
- 12.5 kA short duration rated withstand current;
- 40 ÷ 60 ms opening time;
- 60 ÷ 80 ms closing time.

The analysis was then carried out with a FMEA technique, for the design of experimental tests reproducing typical failure configurations and for the identification of measurement system required. Further details are described in the next paragraph.

**FMEA APPROACH FOR THE DESIGN OF EXPERIMENTAL TESTS**

The aging and loss of performances of circuit breakers depend on many factors, such as number and severity of fault current interruptions, environment, maintenance methods etc [4].

The intention to apply a CBM indicated the FMEA as a powerful standard tool to identify the relationship between system failure/aging and the critical components where the basic failure modes can originate, indicating as well two essential information:

- the type of sensors for the test set;
- the degradation kind of the system to be simulated.

Among the significant examples of FMEA dedicated to switchgears present in literature, the IEEE guide [1] was taken into account as a baseline by ED technicians.

For the equipment under test the revised/adapted FMEA is reported in table 1:

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fails to open or close on command</td>
<td>Open or shorted trip/close coil</td>
</tr>
<tr>
<td></td>
<td>Inappropriate or inadequate lubrication of trip/close latch or mechanism</td>
</tr>
<tr>
<td></td>
<td>Loss of stored interrupting energy</td>
</tr>
<tr>
<td></td>
<td>Trip latch surface wear, deteriorated bearings, or deformation of trip latch flat surfaces</td>
</tr>
<tr>
<td></td>
<td>Defective close coil or solenoid</td>
</tr>
</tbody>
</table>

**Table 1. FMEA of MV switchgear**

Other failure modes and failure causes not indicated in the table were excluded because of the unusual occurrence experienced on service by ED, or for the complexity of relevant on-line monitoring.

Taking into account the content of table 1, the technique of malfunctioning simulation of the system and the number of samples for each configuration is reported in table 2:

<table>
<thead>
<tr>
<th>Failure in trip coil</th>
<th>Simulation Method</th>
<th>N° of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problems</td>
<td>application of incorrect grease on the surface of the electromagnet</td>
<td>3</td>
</tr>
<tr>
<td>Problems in close coil</td>
<td>extraction of armature air gap of the electromagnet (6 mm)</td>
<td>6</td>
</tr>
<tr>
<td>Problems in acting mechanism</td>
<td>application of incorrect grease on the surface of the electromagnet</td>
<td>6</td>
</tr>
<tr>
<td>Problems in close coil</td>
<td>extraction of armature air gap of the electromagnet (10 mm)</td>
<td>3</td>
</tr>
<tr>
<td>Problems in acting mechanism</td>
<td>reduction of the stored interrupting energy, eliminating 1 of the 3 springs in closing mechanism and partial unloading of Opening spring</td>
<td>9</td>
</tr>
</tbody>
</table>

**Table 2. Simulation method of failure on MV switchgear**

The correct functioning state of the equipment, for a comparison with the above failure configurations, was evaluated instead through preliminary tests consisting in:

- 10 samples for coil state
- 12 samples for acting mechanism

**EXPERIMENTAL TEST SET**

The parameters to be recorded in every switching operation and therefore the appropriate type of sensors, were selected on the basis of:

- the components of the system where the failure modes typically originate (as indicated by FMEA);
- the simplicity and cheapness of the measurement system.

It is intended to emphasize the latter point, as the target of this study was the research of a possible industrial application of a diagnostic system, on new and existing
switchgears, based on the on-line monitoring. The requirement was then a non-invasive technique (without open or dismantle parts of circuit breaker), which could be cost-effective though the loss of information when compared with more sophisticated (and more expensive) tests carried out in laboratory. Obviously this compromise fixed at the same time the limits about the maximum state assessment of the supervised equipment.

The parameters eventually chosen for experimental tests were: main contact travel, close and trip coil current, operating times. The analyses and consideration about these measurements are given in the next paragraphs.

A synthetic description of the measurement devices (fig. 2) is given hereafter:

HV Circuit Breaker Analyzer and Microhm-meter “CBA 1000” (produced by ISA s.r.l.)
- operating time accuracy 50 μs
- coil current ranges 2.5; 10; 25 A full scale
- coil current measurement accuracy 0.5% of the reading, ± 0.1% of the selected range
- sample rates 20 kHz – 10 kHz - 2kHz - 200Hz - 100Hz
- timing accuracy 100 μs ± 0.025% of the time range
- maximum record length 200 s

Rotary Potentiometer “P4500” (produced by Novotechnik)
- Electrical angle 350°
- Repeatability to 0.002%
- Independent linearity of +/- 0.075%

Figure 2. Measurement devices used during tests

DATA PROCESSING

The recordings of data in experimental tests were “post-processed” in order to provide an informative content of the equipment state, suitable for diagnostic monitoring.

Parameters evolving in time domain were characterized through the identification of some points on the curves and related secondary derived features, as illustrated in fig 3 and 4 for coil current and mobile contact travel respectively:

Figure 3. Characterization of coil current curve

Other values taken in consideration were the maximum value of instantaneous speed and acceleration, operating times associated to main and auxiliary contacts, for a total number of 24 quantities associated to each switching operation.

ANALYSIS OF RESULTS

The primary distinction on data was made in accordance to the two sub-components identified in FMEA as follows:

1. trip/close coils state → amplitudes and times of appearance from coil current;
2. acting mechanism state → amplitudes and times of appearance from travel curve, speed and acceleration values;

operating times were related instead to both sub-components, taking into account further considerations.

A secondary distinction of data was made between opening and close operations. The analysis of data allowed to select only the “quantities” showing a clear relationship with malfunctioning of the system. The outcome of this analysis was the selection of the following quantities for trip (fig. 5) and close coil assessment (fig. 6-7):

Figure 5. Influence of failure modes on first peak amplitude of trip coil current

Figure 6. Influence of failure modes on amplitude of close coil current when hitting the latch (point P2 of fig 3)
Close coil current absorbed at first peak

```
<table>
<thead>
<tr>
<th>Ampere (A)</th>
<th>1.55</th>
<th>1.60</th>
<th>1.65</th>
<th>1.70</th>
<th>1.75</th>
<th>1.80</th>
<th>1.85</th>
<th>1.90</th>
<th>1.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil correctly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction/wearing of electromagnet surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Incorrect adjustment of electromagnet</td>
<td></td>
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</tbody>
</table>
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**Figure 7.** Influence of failure modes on peak amplitude of close coil current

while for the acting mechanism the following parameters were taken in consideration (it is here reported only the opening switching as the closing one shows a similar trend):

```
<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>linear velocity in first opening phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>maximum velocity</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

**Figure 8.** Influence of failure modes on maximum velocity and linear velocity (between point 1-2 of fig 4)

among the operating times instead, the auxiliary contacts recordings were selected for opening and closing operation:

```
<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>t AUX 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t AUX 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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**Figure 9.** Influence of failure modes on auxiliary contacts timing

From the above results the combination of the parameters with the richest informative content would be:

- amplitude of coil current absorbed at first peak for problems in trip coil
- amplitude of coil current absorbed when hitting the latch for problems in close coil
- linear velocity or maximum velocity for problems in acting mechanism

Nevertheless the eventual selection of the parameters was made on the basis of the purpose expressed throughout this work: the necessity to find a set of parameters suitable for on-line monitoring, requiring an advantageous technical upgrade of the system when compared with the cost of the MV circuit breaker, but at the same time sufficient for planning a condition based maintenance. The amplitude of the coil current absorbed when the electromagnet hits the latch would require indeed a large number of data to be saved and a consecutive post-processing. The travel transducer for the calculation of velocity would imply as well a sensor quite sensitive and expensive to be mounted on the mobile pole, with similar data handling needs of coil current.

For these reasons the exclusion of these extra measurements led to the final choice of the pattern:

- amplitude of coil current absorbed at first peak (easy to calculate by means of a Hall effect sensor and simple data handling in electronic protection devices)
- operating times from auxiliary contact (no hardware modification needed)

The rule of thumb would then be a crossing evaluation of opening times and coil current. A high operating time due to trip/close coil, from diagnosis of its state, would assess the failure to the friction or incorrect position of electromagnet; problems in the acting mechanism would instead be assessed in case of coil correctly working.

**CONCLUSIONS**

The analysis of results obtained encourage to deepen the knowledge of condition monitoring of MV switchgears. Further investigations providing a higher number of data and a following experimental installation on some plants of ED would allow to validate if signalling from such a diagnostic monitoring is reliable to identify the kind of problem on the equipment, optimizing in this way corrective maintenance actions of operational technicians.

**REFERENCES**


