# A computer-aided, reliability-centered maintenance strategy for power networks

**The assessment of the technical condition of substation equipment and its influence on the network is basic to a reliability-centered maintenance strategy. The Electric Power Systems Department at Darmstadt University of Technology and ABB Calor Emag Schaltanlagen AG, Germany, have jointly investigated the theoretical principles of such a strategy and developed a computer program for its implementation. The new software package allows equipment to be ranked according to the order in which it has to be maintained or replaced. It is suitable for a wide range of substation equipment, including switchgear, power transformers and instrument transformers.**

A more competitive market environment is forcing utilities to rethink their repair and maintenance strategies for substation equipment. Economic considerations, in particular, point to the need for solutions which are capable of extending the useful life of the equipment.

At the suggestion of the German utility *Energie-Versorgung Schwaben AG*, the Electric Power Systems Department at Darmstadt University of Technology and ABB Calor Emag Schaltanlagen AG joined together to develop a software package for planning maintenance strategies for high-voltage networks.

Time-based maintenance (TBM) and the replacement of components after their scheduled lifetime has been the standard maintenance strategy of utilities for many years. While this type of maintenance normally achieves acceptable results, it is not always the most economical solution, since the equipment is not generally utilized for the full duration of its potential lifetime. Recent years have seen a trend away from TBM, ie maintenance at fixed intervals, and towards condition-based maintenance (CBM), which is scheduled according to the degree of deterioration of the equipment. A third strategy, reliability-centered maintenace (RCM), is currently receiving a great deal of attention [1, 2]; RCM, besides assessing the technical condition of the equipment, also takes into account the influence of maintenance on the reliability of the network.

**Dr. Gerd Balzer**
**Markus Brandl**
Technische Hochschule Darmstadt

**Dr. Adolf Strnad**
**Heinz Röhsler**
Energie-Versorgung Schwaben AG

**Dr. Armin Schnettler**
ABB Calor Emag Schaltanlagen AG

A maintenance strategy designed to take account of the aspects ‘technical condition’ and ‘reliability’ has to follow a certain procedure [3]:

- The condition of the equipment must be evaluated.
- The importance of the equipment, ie the influence of an outage on the reliability of the power supply, must be known.
- Both items of information have to be combined and evaluated in order to rank the equipment according to its maintenance priority.

**1** illustrates the basic procedure involved. In the following, descriptions are given of the individual steps.

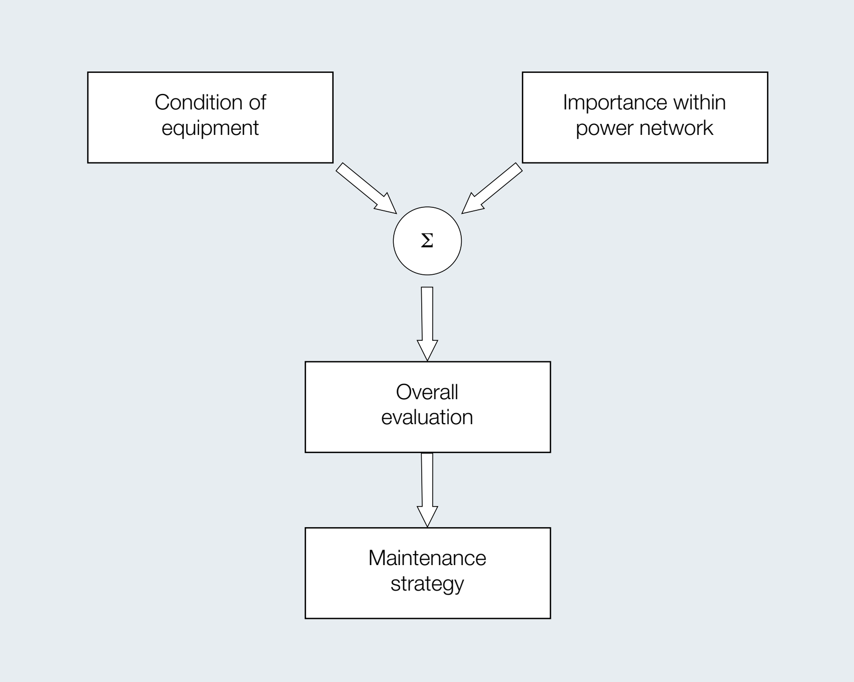
Besides the mentioned maintenance strategies, it is also fundamentally possible to use an event-based strategy, in which equipment is serviced or replaced after a fault has occurred. Such a strategy might even result in the lowest overall costs for equipment requiring only a low capital investment and for which the consequences of a fault are minimal. As a rule, however, event-based maintenance is not employed in high-voltage power systems.

## Effect of substation equipment on availability and the cost of electrical energy

### Availability

A look at the fault statistics for substation equipment can be useful as a means of determining its availability. For example, statistics kept in Germany over a period of many years allow failure rates for the key equipment in substations to be given with some accuracy.

*Table 1* shows the failure rates per year and per 100 installed units over the period from 1980 until 1993. The failure



***Procedure for maintenance planning*** **1**

rates, which are given independently of the vendors, can be seen to depend on the voltage level.

Moreover, the failure rates for entire substations can be calculated using the same statistics. *Table 2* shows the corresponding values for the various voltage levels and different types of substation (air-insulated, indoor, air-insulated and gas-insulated).

When the total number of substations and the total equipment of different types installed throughout the network are known, it is possible to calculate an average number for each type of equipment per substation. Combining these values with the failure rates in *Table 1*, the percentage of total faults caused by the different types of equipment can be determined, referred in each case to the total number of faults occurring in a substation.

The result is a ranking indicating the types of equipment that cause the most failures in HV substations. For example, in a 420-kV substation about 35 % of all failures are caused by circuit-breakers, followed by instrument transformers with 11.4 % and power transformers with 9.4 %. To obtain a final ranking, the average number of each item of equipment per substation has to be considered. As already mentioned, about 11.4% of the failures are caused by current transformers; in a 420-kV substation, however, there are approximately 34 CTs, whereas approximately the same percentage of failures is caused by an average of 1.8 units in the case of the power transformers.

The above considerations show that the following types of equipment are the main contributors to the overall failure rate of substations:

- Circuit-breakers
- Power transformers
- Instrument transformers
- Disconnectors

This is therefore the equipment which always has to be considered when developing a maintenance strategy, whereby the first two are responsible for the majority of the failures.

### Cost

Besides the availability of the equipment, the cost of the components also plays an important role in the evaluation of a maintenance strategy. Thus, the equipment listed above also has to be looked at from this standpoint.

### Software for maintenance strategies

In general, software for maintenance strategies has to take the following two aspects into account [4]:

**Table 1:**
**Failure rates of equipment from different German manufacturers per year (1980 – 1993) and per 100 installed units**

| Equipment | | $U_n$ (kV) | |
|---|---|---|---|
| | 110 | 220 | 380 |
| Circuit-breaker | 0.238 | 1.179 | 2.359 |
| On-load switch | 0.167 | – | – |
| Disconnector [1] | 0.043 | 0.089 | 0.156 |
| Earthing switch [1] | 0.029 | 0.046 | 0.027 |
| Transformer | 0.365 | 1.537 | 2.069 |
| Voltage transformer | 0.035 | 0.068 | 0.113 |
| Current transformer | 0.020 | 0.047 | 0.147 |
| Combined instrument transformer | 0.049 | 0.116 | 0.095 |
| Surge arrester | 0.149 | 0.329 | 0.391 |

[1] 1984 – 1993

**Table 2:**
**Failure rates[1] for 100 German HV substations from different vendors per year during the period 1980 – 1993**

| Substation | | $U_n$ (kV) | |
|---|---|---|---|
| | 110 | 220 | 380 |
| AIS | 8.517 | 24.824 | 40.655 |
| Indoor AIS | 7.744 | – | – |
| GIS | 5.037 | 3.106 | 17.296 |
| *Substation (ave value)* | *8.153* | *24.641* | *38.710* |

[1] Total number of failures in one year (average values) divided by the total number of substations at this voltage level

- The technical condition of the equipment
- Importance of the equipment in terms of its effect on the network condition

Taking a circuit-breaker as an example, these two aspects and the adopted approach will now be looked at more closely.

### Technical condition

The technical condition of a circuit-breaker can be evaluated on the basis of different criteria, some of which are listed in *Table 3*. In addition, rating and weighting factors have to be applied to take account of the influence of each criterion on the overall value *c* representing the technical condition of the equipment **2**. The lower the number, the better the technical condition. For such listings, it makes sense to fix a number such as 100 as the maximum attainable figure.

*Table 3*, for example, lists a small section of the items of interest for the assessment of a circuit-breaker. The individual criteria can be set or adapted according to the specific experience of the equipment user. Also, the results of typical measurements carried out on the equipment can be referred to in the assessment, as shown in the last line of *Table 3*. Examples are the operating time, gas and oil analyses, tightness, and synchronism of the contact switching. A separate evaluation sheet can also be drawn up for these individual measurements, and the result of the evaluation included in the total assessment based on *Table 3*.

### Importance of equipment in terms of its effect on the network condition

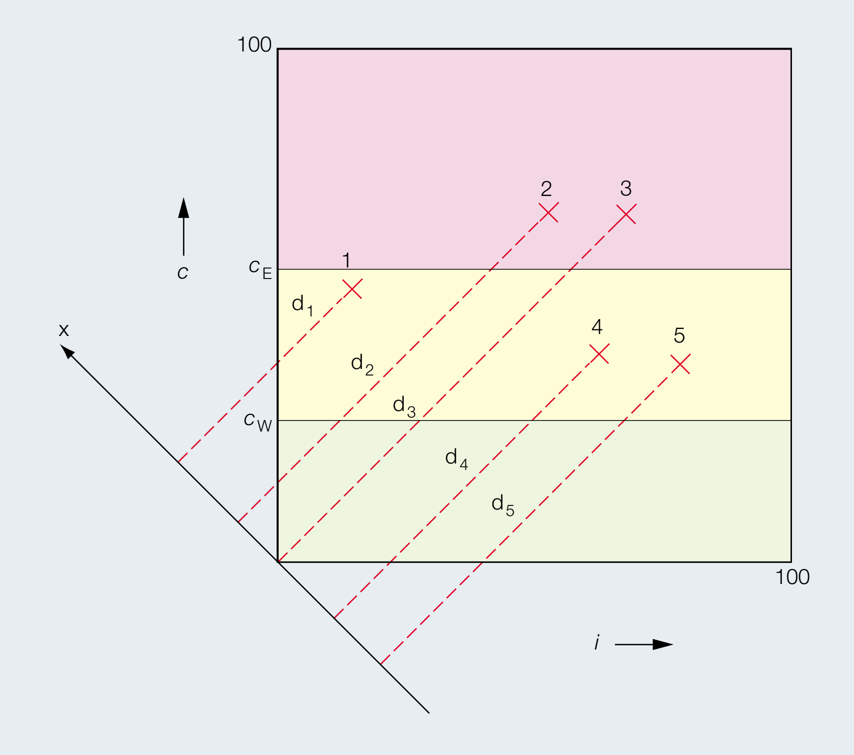
The importance of a circuit-breaker in terms of how it may affect the condition of the overall network can be estimated with the help of the following equation:

$$i = Q \cdot p = (\lambda\, T_a) \cdot p \qquad (1)$$

| | |
|---|---|
| $Q$ | Non-availability of component |
| $p$ | Factor used to determine loss of power |
| $\lambda$ | Failure rate of component due to damage caused by fault |
| $T_a$ | Outage [h] (switching/repair time) |

**Table 3:**
**Data sheet for the assessment of circuit-breakers (extract)**

| Criterion | Rating | | Weighting | Result |
|---|---|---|---|---|
| Age | <20 | 1 | 1 | |
| | 20–25 | 2 | | |
| | 26–30 | 3 | | |
| | 31–35 | 4 | | |
| | 36–40 | 5 | | |
| | >40 | 6 | | |
| Experience with this type of circuit-breaker | good | 1 | 3 | |
| | ... | ... | | |
| | bad | 6 | | |
| Maximum short-circuit capability | <80 % | 1 | 3 | |
| | 80–90 % | 2 | | |
| | 91–99 % | 3 | | |
| Number of switching operations | low | 1 | 1 | |
| | ... | . | | |
| | ... | . | | |
| | high | 6 | | |
| Number of short-circuit interruptions | low | 1 | 2 | |
| | ... | 2 | | |
| | high | 3 | | |
| Type of circuit-breaker | $SF_6$ | 1 | 1 | |
| | minimum oil | 3 | | |
| | air | 4 | | |
| Measurement results | good | 1 | 4 | |
| | ... | ... | | |
| | bad | 6 | | |



***Interpretation of the results of the evaluation*** **2**

| | |
|---|---|
| $c$ | *Technical condition of equipment* |
| $c_E$, $c_W$ | *Characteristics* |
| $i$ | *Importance of equipment* |
| $d_1 \dots d_5$ | *Sequence in which equipment within an area is to be maintained/replaced* |

The failure rate of a circuit-breaker is obtained, for example, by evaluating the network statistics or by referring to empirical values. Adding these to the data in *Table 1*, the failure rates can be determined as a function of the circuit-breaker type and the nominal voltage of the network.

The outage $T_a$ of a component is either the repair time ($T_p$) or the switching time ($T_s$), whichever is the shorter. $T_a$ is dependent upon the circuit-breaker duty, ie where it is installed (overhead line, transformer, power station, coupling feeder, etc). Thus, $T_a$ is rated quite differently for a reactor circuit-breaker than for an overhead line feeder, which satisfies the ($n$–1) planning principle.

The non-availability $Q$ is weighted according to the power outage in order to define the importance of the circuit-breaker in the network. Here, the actual outage $P_{out}$ caused by the fault is considered. The load factor $p$ is given by:

$$p = \left(1 + n \frac{P_{out}}{P_{max}}\right) \qquad (2)$$

| | |
|---|---|
| $P_{out}$ | Power outage due to failure of the component |
| $P_{max}$ | Maximum power outage within supply area possible due to failure of a circuit-breaker |
| $n$ | Normalizing factor |

The normalizing factor $n$ in eqn (2) is chosen such that the value $i$ as per eqn (1) may have a maximum value of 100.

A high value for $i$ according to eqn (1) means that the condition of the equipment has a major influence on the network.

### Interpretation of the results

After the values for the two parameters $c$ and $i$ have been calculated, they can be entered (as crosses) in a plot **2**. The vertical axis indicates the technical condition of the equipment and the horizontal axis the extent of its influence on the network. A cross in the top left corner represents a component which, although in poor technical condition, would not have any major consequences if it should fail. On the other hand, a cross in the bottom right half indicates a component which is in a very good technical condition. Failure of this component would have considerable consequences for the operation of the network. The distances $d_1$ to $d_5$ (to the $x$-axis) illustrate the priority which has to be given to maintenance or replacement of the individual circuit-breakers. In the example shown, breaker 3 should be maintained first, followed by breakers 2, 5, 4 and 1.

The characteristics $c_W$ and $c_E$ are entered on the basis of empirical network data, eg user-specific data. Lines parallel to the abscissa $i$ and passing through the characteristics define the areas in which maintenance or replacement is necessary for technical reasons.

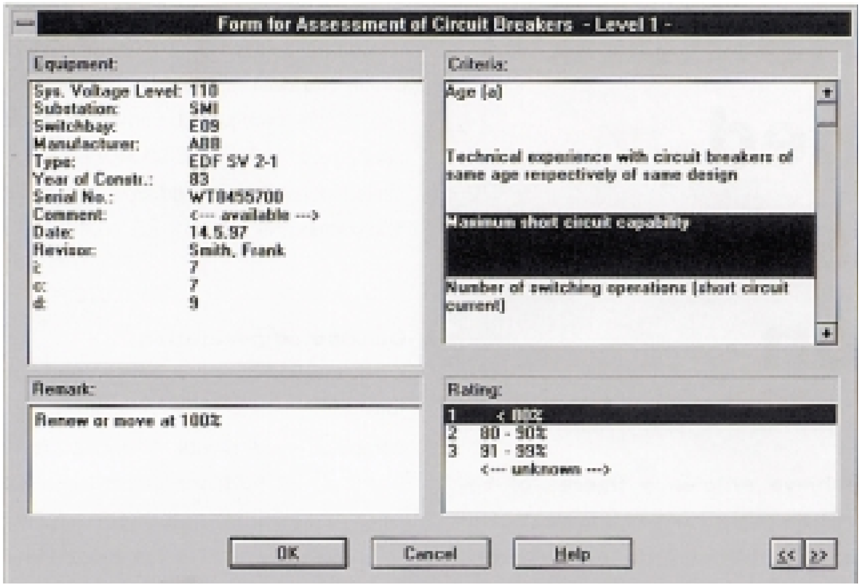
The allocation of the areas can now be defined as follows **2**:

$100 - c_E$: Replacement
$c_E - c_W$: Maintenance
$< c_W$: No action required

Within any one of these areas, the priority for the different measures is given by the distances to line $x$.

### Description of the software

The input window of the developed software **3** allows user-friendly evaluation of the technical condition of a component. The user can assess the individual criteria by referring to lists of different evaluation options and select the required variant. As an option, default values can be



Equipment:

Sys. Voltage Level: 110
Substation: SMI
Switchbay: E09
Manufacturer: ABB
Type: EDF SV 2-1
Year of Constr.: 83
Serial No.: WT0455700
Comment: <--- available --->
Date: 14.5.97
Revisor: Smith, Frank
i: 7
c: 7
d: 9

Criteria:

Age (a)
Technical experience with circuit breakers of same age respectively of same design
Maximum short circuit capability
Number of switching operations (short circuit current)

Remark:

Renew or move at 100%

Rating:

1 < 80%
2 80 - 90%
3 91 - 99%
<--- unknown --->

*Input window of the developed software* **3**

chosen, or special values typical for this component can be entered in order to determine the variables $\lambda$ and $T_a$ as per eqn (1).

The evaluation lists can be divided into 'must' and 'can' areas, whereby a 'must' criterion always has to be entered to allow an evaluation to be made. If, on the other hand, there is no response to a 'can' criterion (eg measurement results), the final ranking is corrected accordingly.

**4** shows a screenshot of the main window. On the left-hand side is an extract from the list of circuit-breakers known to the software, together with their main data, eg the manufacturer, substation, serial number, system voltage, etc. The list of criteria on the far right allows the user to choose from the total data inventory. With the help of this window, the equipment operating at a certain voltage level, in a certain substation, or from a certain manufacturer, can be selected and evaluated. A graphic representation of the calculated results as per **2** is shown in the center of the screen. Selected circuit-breakers are highlighted and shown coloured in the list on the left-hand side.

## References

[1] Moubrary: Reliability centered maintenance. Butterworth Ltd, Oxford (1992).
[2] RCM and diagnostics. EPRI Seminar on Reliability Centered Maintenance. Newport Beach, CA, USA (1995).
[3] A. Strnad, H. Röhsler, et al: Strategy for condition based maintenance and updating of substations. CIGRE 1996, 23–105.
[4] T. Kawamura, M. Horikoshi, S. Kobayashi, K. Hamamoto: Progress of substation maintenance. CIGRE 1990, 23–102.

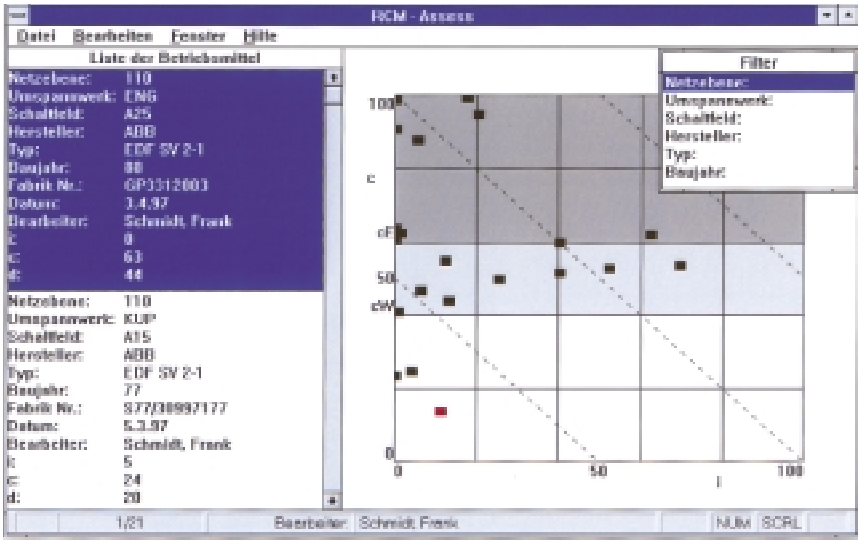
## Authors' addresses

Dr. Gerd Balzer
Markus Brandl
Technische Hochschule Darmstadt
Landgraf-Georg-Strasse 4
D-64283 Darmstadt
Germany

Dr. Adolf Strnad
Heinz Röhsler
Energie-Versorgung Schwaben AG
Kriegsbergstrasse 32
D-70174 Stuttgart
Germany

Dr. Armin Schnettler
ABB Calor Emag Schaltanlagen AG
P.O. box 100 351
D-68128 Mannheim
Germany
Telefax: +49 621 386 2785
E-mail:
armin.schnettler@deace.mail.abb.com

*Main window showing a graphic representation of the results* **4**



Netzebene: 110
Umspannwerk: ENG
Schaltfeld: A25
Hersteller: ABB
Typ: EDF SV 2-1
Baujahr: 88
Fabrik Nr.: GP3312003
Datum: 3.4.97
Bearbeiter: Schmidt, Frank
i: 0
c: 63
d: 44

Netzebene: 110
Umspannwerk: KUP
Schaltfeld: A15
Hersteller: ABB
Typ: EDF SV 2-1
Baujahr: 77
Fabrik Nr.: S77/30997177
Datum: 5.3.97
Bearbeiter: Schmidt, Frank
i: 5
c: 24
d: 20

Bearbeiter: Schmidt, Frank