RELIABILITY CENTERED MAINTENANCE STRATEGY FOR MV-SUBSTATIONS

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INTRODUCTION

In view of the changing macro-economic and ecological context in the power industry, it is worth thinking about extending the lifetime of equipment and reducing maintenance costs in power networks. What options are there? Advanced diagnostic tools can offer very precise and important additional information for evaluating the equipment's technical condition. They are the basis for computer-aided maintenance optimization, which today give very reliable results.

MAINTENANCE STRATEGIES

A more competitive market environment is forcing the utilities to rethink their repair and maintenance strategies for network and substation equipment. Economic considerations, shows, point to the need for solutions which are capable to extend the lifetime of the equipment. Generally, the maintenance of equipment or systems concerns the following tasks:

- Inspection: Determining and assessing the actual condition
- Servicing: preserving the desired condition
- Repair: restoring the desired condition
- Replacement: replacing equipment or systems which are no longer usable

The following maintenance strategies are in use:

- corrective
- time-based
- condition-based
- reliability-centered

In a *corrective maintenance* (CM) strategy, replacement or repair is performed only if occurred. In the case of equipment where investment costs are low and a fault will have only a minor effect, this procedure may result in the lowest overall costs.

A *time-based* maintenance (TBM) strategy featuring predefined intervals rooted in empirical feedback, where components are replaced after a specified period of use, has for many years been practised as the usual maintenance strategy in electricity supply networks. This approach generally produces satisfactory results. It will not, however, be the most cost-effective option in all cases, since the equipment will not usually remain in operation up to the end of the lifetime actually possible.

Since some years, however, there has been a developing shift away from time-based maintenance and towards *condition-based* maintenance. Condition-based maintenance (CBM) is driven by the technical condition of the equipment. Under this approach, all major parameters are considered in order to determine the condition with maximized accuracy.

A fourth strategy, which additionally include a reliability-based component, has been under discussion recently, and some applications are reported here. The aim of this approach is to incorporate the influence on the reliability of supply and the importance of the equipment in the network and the actual condition of the equipment. A maintenance strategy which allows for these factors as well is referred to in this paper as reliability centered maintenance (RCM) /1, 2/.

A reliabilitiy centered maintenance strategy combining the two aspects of condition and importance necessitates the following procedure /3, 4, 5, 6/:

- The condition of the equipment has to be determined.
- The importance of the equipment for the network as a whole must be determined, e.g. the influence of equipment failure on the reliability of supply.
- Both information inputs must be combined and evaluated in order to specify the optimum sequence of maintenance work for the individual devices (equipment, substation).

The reliability of supply is influenced by the type of maintenance strategy applied. Figure 1 shows the effects on network reliability comparing for the different strategies in the networks nowadays. Without a doubt, the RCM strategy (a more advanced version of the CBM strategy, if the constraints due to the restricted financial resources have to be considered) offers definite advantages, since besides the condition of an equipment or a system, its importance in the network also crucially influences the maintenance action required. It clearly emerges that network reliability can be upgraded by correct selection of the equipment for maintenance.

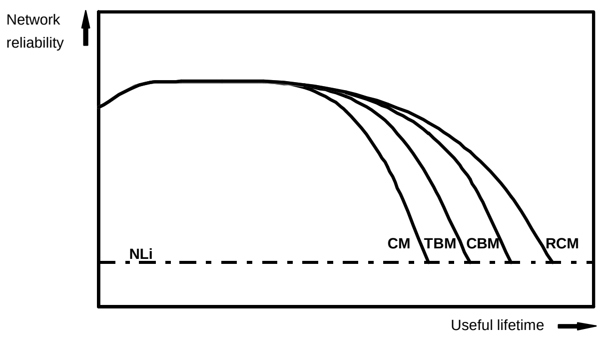

Figure 1: Network reliability comparing different maintenance strategies
CM: corrective
TBM: time-based
CBM: condition-based
RCM: reliability centred
Nli: limit of network reliability

THE REQUIRED EQUIPMENT DATA

General

In the medium voltage range the whole substation should be assessed to make a ranking for maintenance. In contrary to the high voltage system, where single equipments are evaluated e.g. for an air-insulated substation due to the number of parts with higher investment costs.

Condition

On this reason the following items has to be considered for a M.V. substation:

- substation bays (in general)
- circuit-breakers
- disconnector
- switch-disconnector
- instrument transfomers (current, voltage)
- power transformers (medium/low-voltage)
- resonant-coils
- secondary equipments (e.g. protection, control)
- auxilary voltage equipments
- telecontrol
- building.

This above mentioned parts have to be combined in an appropiate manner to assess the complete M.V.-substation. The assessment can be performed for example due to the number and investment costs of each item.

As a first step, the equipment's condition is assessed on the reason of selected criteria. In addition, evaluation and weighting factors are useful, defining the influence of each criterion on the overall condition for the equipment concerned. The points calculated on this basis are a measure for the condition involved. The lower the number of points, the better is the condition concerned. It will be found helpful here to scale the maximum achievable number of points to 100, for example.

As an example, Table 1 lists a small proportion of the possible criteria of interest for assessing the whole substation. In this case only some criterias are mentioned describing the circuit-breaker (table 1a), protection (1b) and building (1c). The individual evaluation criteria and weightings for each item can here be differently defined or supplemented in dependence on the operational experience of individual users of network installations.

The different parts have to be compared to assess the complete substation. One possibility is to use the costs of a new investment for the weighting factor G. Table 2 summarized the data combining the following values:

- condition (c)
- number of each equipment (n)
- weighting factor G comparing the different equipment.

The different values c, n, and G have to be multiplied and added according to table 2 making an overall ranking of the complete substation.

a

Criterion	Evaluation		V	W	R
Age (in years)	<20 20-35 26-30 31-35 36-40 >40	1 2 3 4 5 6	4	1	4
Experience with the same type	very good ... medium ... poor	1 2 3 4 5	3	5	15
Total number of switching operations p. a.	normal (≤ 3) medium (≤ 6) high (>6)	1 3 5	1	3	3
Breaker type	vacuum SF_6 minimum Oil air	1 2 3 6	3	4	12
Spare parts supply	good medium poor	1 3 5	3	2	6

b

Criterion	Evaluation		V	W	R
Age (in years)	<20 20-35 26-30 31-35 36-40 >40	1 2 3 4 5 6	5	1	5
Type	digital electronic electromech.	1 4 5	5	5	25
xperience with the same type	very good ... medium ... poor	1 2 3 4 5	3	5	15
Amount of same type in the ntework	high medium low	1 3 5	5	4	20

c

Criterion	Evaluation		V	W	R
Age (in years)	<20 20-35 26-30 31-35 36-40 >40	1 2 3 4 5 6	4	1	4
maint. costs compared with investment costs each year	< 40 % 40 - 70 % > 70 %	1 2 3	3	4	12
Pressure relief	yes no	1 6	6	4	24
Type, con-struction	massive prefabricated steel	1 2 5	1	2	2
Roof	saddleback flat	1 6	6	5	30

Table 1: Excerpt from assessment sheets
a circuit-breaker
b protection, control
c building
V Value R Result
W Weighting

For example, the considered substation has 24 bays, 21 circuit-breakers, and 4 voltage transformers. The assess-ment of the condition covers a range from 0 (excellent) to 100 (bad) points. According to this the condition of the bays is bad (83 points) whereas the remote control is good (20 points). The assessment of the complete substation leads to the result of 60 points. The last column of table 2 gives an overview which equipment of the substation has the main impact on the condition in percent. In this case, the result is:

- protection, control, monitoring (26 %)
- bays, configuration (22 %)
- building (22 %)
- circuit-breaker (10 %)

Equipment		c	n	G	R/%
primary equipment	Bay/Configuration	83	24	1.00	22
	Circuit-breaker	44	21	1.00	10
	Voltage transformer	64	4	0.27	1
	Current transformer	20	20	0.27	1
	Disconnector	57	72	0.13	6
	Switch-disconnector	22	4	0.50	0
secondary equipment	Protection, control, monitoring	73	24	1.33	26
	Auxilary voltage	73	1	1.33	1
	Telecontrol	30	24	0.17	1
Others	Transformer	49	2	0.33	0
	Resonant coil	35	2	5.00	4
	Remote control	20	2	8.33	4
	Building	81	24	1.00	22

Table 2: Final result of the condition, M.V. substation no. 1 (table 4)
c condition of the different equip-ments
n number of equipments or bays within the substation
G weighting factor
R result in percent

Importance

Defining an equipment's importance and assessing the consequences of a fault basically constitute a practical but also subjectively influenced value judgement. In this context, there are numerous different parameters to be considered:

- substation configuration: single or double busbar with or without coupling
- feeding voltage, e.g. 110 kV
- active power
- kind of customers: household, small or big industries
- non-availability of the substation
- compensation of the interrupted active power.

The non-availability of the substation should be evaluated according to the experiences of the user considering the different types. For example the reliability of substations is recorded in Germany since many years. Table 3 shows the outage rates of different type of substations. Metalclad means insulation- as well as SF_6-enclosed.

type	12 kV	24 kV
outdoor (open air)	0.189	0.786
indoor (open air)	0.010	0.026
metalclad	0.050	0.078

Table 3: Outage rates (per year) of different substations according to the rated voltages

It must be decided from case to case which of these parameters are to be taken into account, or what combinations of different parameters are determinant.

OVERALL ASSESSMENT

Figure 2 shows the basic procedure for linking the two assessment criteria:

- condition of the equipment
- importance of the equipment in the network

Both these criteria are combined in an appropriate manner enabling an overall assessment to be arrived at.

After the values for the "*c*" (condition) and "*i*" (importance) parameters have been calculated, the results (crosses) can be listed in an X, Y system of coordinates, as shown in Figure 3. The "*c*" and "*i*" axes are scaled in such a way that the "*c*" and "*i*" values can at maximum assume the value 100. A large value for "i" signifies that the equipment concerned is of high importance in the network.

The vertical axis represents the condition of the substation concerned, while the horizontal axis reflects its importance in the network. A cross in the top left-hand corner corresponds to a substation which, although in a poor technical condition, would not cause any major consequences if it fails. By contrast, a cross in the bottom right-hand corner designates a substation which is in very good condition. A failure of this device would entail substantial consequences for network operation. The distances d_1 to d_5 illustrate the sequence in which the individual substation must be serviced or replaced.

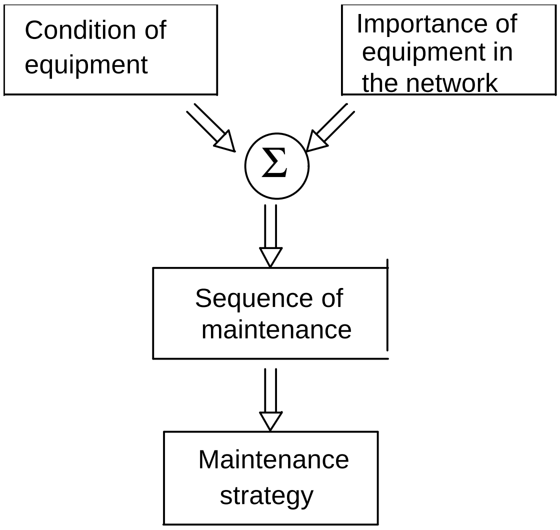

Figure 2: Procedure for maintenance planning

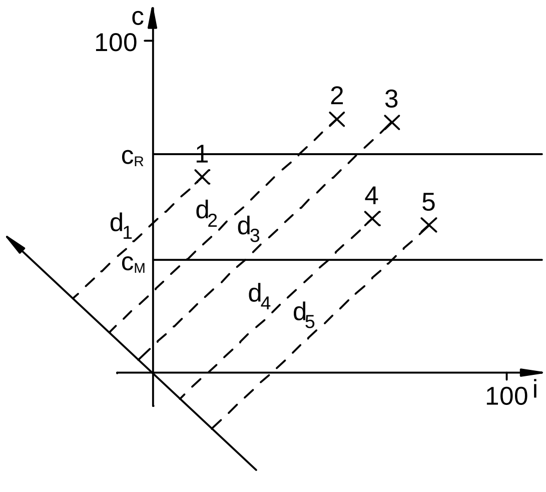

Figure 3: Interpretation of the assessment result
c technical condition of the substation
i importance of the substation

COMPARISON WITH PREVIOUS PRACTICE

The evaluation levels c_M and c_R are entered in Figure 3 in accordance with empirical feedback from the network engineers concerned, i.e. as user-specific data. The parallels to abscissa "*i*" through c_M and c_R characteristics delimit the areas in which from a technical viewpoint a servicing routine or replacement is required. Area assignment can be defined as follows:

100 - c_R:	replacement
c_R - c_M:	maintenance, repair
< c_M:	no action required

Inside a particular area, the priority for individual measures is obtained by examining the distances d from the straight line.

Figure 3 also makes clear, assessing the condition is not of itself sufficient for maintenance planning. For example, servicing of substation 5 would be more necessary than for substations 1 and 4, although substation 1 shows a bad condition.

With the aid of the classification achieved in Figure 3 the necessary maintenance action can be specified. Basically, it is also possible to specify an area of event-driven maintenance in this scheme, i.e. an area in which all the substations needed to be replaced only after a malfunction. These substations are characterized by being below a critical importance threshold, so that a failure has no significant effect on network reliability. In addition, it should be possible in future to subdivide the "< c_M" area further, so different inspection intervals can be defined.

Both reliability-centered and condition-based maintenance strategies require the same data for assessing the condition of the equipment. Of course, many equipment/network-specific data can be collected for evaluation. In practice, however, they must be restricted to the major influencing variables, for which there is actually utilizable information derived from the process, from relevant statistics, or from manufacturer's documentation. Results are crucially dependent on assessment of the individual criteria involved in evaluating a particular equipment, and the weightings assigned to them.

Empirical feedback meanwhile obtained in regard to maintenance planning indicates that particular attention should be paid to determining the levels c_R and c_M. This in turn necessitates good feedback to condition estimates by equipment specialists at the manufacturers, the network operators and the maintenance engineers. For determining/calibrating the levels c_R and c_M, a minimum number of substations for evaluation is accordingly essential. This must always be borne in mind when adding any further criteria.

The assessment of the whole substation can be regarded as the first step considering the maintenance strategy. According to table 2 the influence of each equipment of the substation on the overall result can be evaluated. And therefor the replacement of this equipment and its impact on the whole assessment
can be calculated in a second step. On this reason the decision can be made to replace the complete substation or only the single equipment to get an acceptable result of the technical assessment.

The first stage in planning work covers M.V. substations; M.V. Stationen are incorporated in RCM planning as a further component in the network. Even ¨though very encouraging results have been obtained overall, it must be remembered that, as when any other new work process is introduced, it is important and advisable to provide effective information on, and reasons for the advantages accuring to the departments involved. It can be stated that RCM planning has constituted a major advance on the path towards optimally cost-efficient network operation.

EXAMPLES

On the basis of the principles according to chapter 2 six M.V. substations are assessed. The main data of the substations are listed in table 4. All substations are of the air insulated type (indoor).

substation	year	H.V..
1	1958	yes
2	1954/55	yes
3	1963/64	yes
4	1962	no
5	1972	yes
6	1971	yes

Table 4: Main characteristic data of the considered 20 kV substations

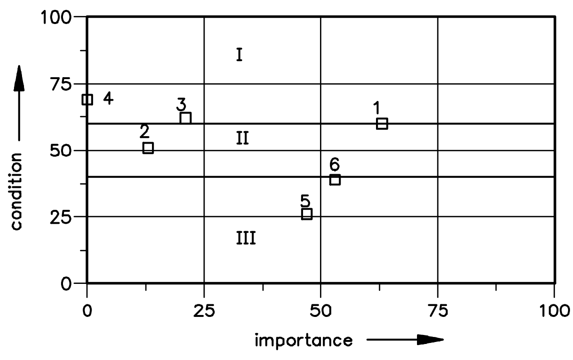

Figure 4: Final result of the assessment of M.V. substations
□ substations 1 - 6 (table 5)
I area: replacement
II area: maintenance, repair
III area: no action

The final result of the assessment is shown in fig. 4,

if the area assignment is defined as

100 - 60:	replacement (area *I*)
59 - 40:	maintenance, repair (area *II*)
< 40:	no action required (area *III*)

in a first step. The ranking of the substations due to maintenance activities is according table 5.

The result of the assessment is, that three of the considered substations should be replaced and the ranking is substation no. 1 - 4 - 3. Due to the importance of substation 1 (d = 87) this substation has the highest priority although the technical condition is better than the other one (c = 60).

strategy	c	overall ranking	d	sub-station	main impact
replacement	60	1	87	1	protection, building
	62	4	58	4	protection, bays
	69	2	49	3	protection, bays
maintenance	51	6	46	2	protection, bays
no action	39	3	65	6	protection, building
	26	5	52	5	protection, circuit-breaker

Table 5: Final result of the assessment and maintenance strategy
c condition of the substation
d final assessment (condition and importance)

In any case the condition of the protection has the main impact on the condition of the substations as listed in the last column of table 5. The reason is, that the electromechanic protection has an important influence of the assessment, according to table 1b compared with the other protection types.

According to figure 4 an area of corrective maintenance can be defined if for example substations with a lower importance of i = 10 belongs to this group. In this case substation no. 4 should not replaced according to the importance of i = 1.

As mentioned before the complete substation no. 1 has to be replaced and furthermore it should be advisable to renew the building too, according to the assessment of the relevant row of table 2.

OUTLOOK AND SUMMARY

When looking at this optimized process design concept, the time needed to achieve this goal should not be underestimated. Since, however, the procedure for the basic and crucial core process of network component evaluation has already been defined, and an appropriate PC program (CALPOS®-Main) for this purpose are already available for high voltage equipments on the market. The program module for m.v. substations will be developed in a very short time, the resultant advantages as presented in this paper can be effectively exploited here and now. Further development of CALPOS®-Main is targeting not only the automatic incorporation of time-dependent evaluation parameters, but also an option with an upstream fuzzy application.

It is decided to integrate CALPOS®-Main into maintenance management systems. In the final analysis, computerized maintenance planning in a company necessitates a shared database, to serve as a foundation for both maintenance planning and a higher-order information system for the network.

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/ Strnad, A.; Röhsler, H.; et. al.: Strategy for Condition based Maintenance and Updating of Substations. CIGRE 1996, 23-105

/4/ Balzer, G.; Brandl, M.; Strnad, A.; Röhsler, H.; Schnettler, A.: Rechnergestützte Wartungs-strategie für Schaltanlagen. ETG-Fachbericht 66(1997), S. 99 - 111

/5/ Balzer, G.; Brandl, M.; Strnad, A.; Röhsler, H.; Schnettler, A.: A computer-aided, reliability-centered maintenance strategy for power networks. ABB-Review 4/1997, p. 21 - 25

/6/ Balzer, G.; Strnad, A.; Schnettler, A.; Schmitt, O.: Decision Supporting Software Tool for an Optimised Maintenance Strategy. CEPSI '98, Thailand, report 31-38