CONSIDERATION REGARDING THE RELIABILITY CENTRED MAINTENANCE OF ELECTRIC POWER TRANSFORMERS

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INTRODUCTION

The paper is based on the experience of authors in maintenance systems implementation for reliability of power transformers from an Electric Power Distribution Department.

The paper is structured in three parts. In the first part are presented general considerations for system reliability centered maintenance (RCM) and specific particularizing for the distribution grids structure equipment. The vision of authors is to apply RCM, which involves estimates and actions good to execute maintenance works, in correlation with a stabilized reliability level (forecast) or determined (symbolic).

The second part contains references of RCM strategies application methodologies to power transformers (PT). As starting point we propose the PT functions explanations in EPDS. Depending on the intrinsic scale gravity \( k \) as well on frequency scale \( f \) of failures, the authors define and apply for power transformers RCM a scale of efficiency get used to tackle EPDS. The optimizing criteria are the cost related with the minimal unavailability period \( \gamma \). In the paper are presented the results obtained for Bihor EPDS.

In the third part of the paper are the studies results presented referring on RCM for PT from Bihor’s EPDS. Since 1990, Department of Distribution, Supply of Power Energy Bihor manages in framework Bihors’ PS the power’s transporting, distributing and supply subsystems. DDSPE established a new method to affect the operational reliability studies, which characteristics and results were the objects of many published papers.

1. Reliability Centred Maintenance

In order to be able to accomplish the maintenance objectives, it is very important to be aware of the various methods of maintenance and make the most adequate selection adapted to the requirements and demands of each type of installation. A general classification of maintenance policies points out two main categories: the maintenance which restores the installation after a defect, named as corrective maintenance (CM), and the second type, which avoids the defect, named as preventive maintenance (PM) [1]. The employment of both methods is the mixed maintenance (MM).

The first scientific approaches of maintenance date back to 1950 ÷ 1960. In that time PM was considered as a mean to reduce the defects and breakdown duration. The well-known models consisted in the replacement of the whole block (unit). In the seventies were implemented the defect prediction techniques by vibration monitoring, and in eighties, was introduced the computer in maintenance management activities.

An example of the scientific management of maintenance is the Reliability Centred Maintenance (RCM). According to the present standard [6,8] as a first step- RCM is appropriate to maintenance policies that identify the critical elements of the operational installations, in which failing has a considerable impact on the proposed objectives (safety, availability, costs, maintainability). RCMs’ objective is to avoid the failing of critical elements, with effects that are reflected on the direct and indirect exploitation costs.

In the second stage are identified those elements, although operational, which announce an imminent defect, for which the monitoring and diagnosis methods are used.

An efficient maintenance program, in the RCM concept, plans only those procedures that necessary in order to accomplish the proposed objective in the operating system.

Compared with the two, aforementioned, dedicated directions of RCM, the actual practice justifies the following definition of this maintenance strategy: RCM consists in assessments and actions required in the maintenance activities according to an imposed (envisioned) or constant (operational) reliability level. RCM targets mainly procedures of preventive maintenance, and, eventually, optimised approaches of mixed maintenance. For an analytical approach of RCM is necessary to know the real level of operational reliability, which is, obviously, obtained from studies, having a clearly defined space and time localisation. For the equipment compounding the structure of power systems (PS) the principal aspects approached and treated appropriately with RCM actions are:

- determine the optimal frequency of testing, in order to minimise unavailability time [3,4,5];
• application of replacement policies according to status [6,8];
• optimal management of “k from n” type structures [4,6,10];
• optimal weighted, structural and temporal, of works from (PM + CM) categories, in case of mixed maintenance strategy [4,11,12];
• optimisation of the level of stocks of equipment, spare parts and materials [4];
• diagnosis of the technical status by adequate monitoring [4,5,6].

RCM is only one of the means used in current practice, in agreement with the principles of reengineering of the systems, in order to accomplish a certain level of performance.

In general, depending of the (pre-set and set) level of performance attributes (reliability, availability, costs, etc.) are recommended hierarchical degrees of analysis and diagnosis of the systems. This approach requires the knowledge of the indices of reliability, availability, maintainability and economic efficiency of the installation (subsystem) and of the system in which is integrated.

According to the aforementioned principles, for the power distribution and supply systems (DSPS) are required the following:

• Hierarchisation of the equipment within the structure of DSPS according to the economic importance of their reliability. In this sense, are recommended the following indicators:

\[
C_v = \frac{\cos ts}{\text{int. eruption}}; \quad C_p = \frac{\cos ts}{\text{int. eruption hour}}
\]

(1)

\[
\alpha = \frac{v(T_A) \cdot C_v}{C_v}; \quad \beta = \frac{\beta(T_A) \cdot C_p}{C_p}; \quad \gamma = \alpha + \beta
\]

(2)

where:

- \(C_v\) total cost (acquisition, installation, and maintenance) of equipment
- \(v(T_A)\), \(\beta(T_A)\) – number and date of interruptions within the analysed period

TABLE 1 – Intrinsic and extrinsic gravity scale (k)

<table>
<thead>
<tr>
<th>Gravity scale</th>
<th>Effects of PT functions</th>
<th>Consequences to power energy consumers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = low (without gravity)</td>
<td>The functions are not affected (ex. failing of any element of the mechanical consolidation)</td>
<td>Reduced and medium economic consequences</td>
</tr>
<tr>
<td>2 = medium (dangerous)</td>
<td>Are effected in acceptable limits (allowed by norms and operating conditions) functions (f_1) and (f_4) (ex. effect on the magnetic subsystem)</td>
<td>High economic consequences and low social consequences</td>
</tr>
<tr>
<td>3 = high (high gravity)</td>
<td>Functions (f_2), (f_3), (f_4) are decisively affected (ex. break of insulation)</td>
<td>High social consequences</td>
</tr>
<tr>
<td>4 = very high (very dangerous)</td>
<td>(f_1) function is affected</td>
<td>Ecological consequences and effects on human life.</td>
</tr>
</tbody>
</table>

- In the framework of DSPS will be set-up the maintenance staff with management role of strategies and implementation of the economically founded maintenance techniques.
- A study using AFEM (analysis of the means of defects and their effect) shall be carried out paying special attention to the equipment with certain level of economic importance of reliability. In this case will be established the gravity level \(k\) of the result and the frequency \(f\) of appearance for every failing mode, with indication to all selected equipment, which allows the estimation of the unsafety indicator: \(p = f \times k\).
- Referring to the failing modes and the maintenance operations of the equipment, are estimated in fuzzy mode the following:
  - Efficiency \((e) = \text{capacity of identification of a failing mode by a given diagnosis method;}\)
  - Simplicity \((s) = \text{the ability to put in practice a certain diagnosis technique or/and a maintenance operation;}\)
  - Usability \((a) = e \times s\)
- Based on the above results there will be determined the equipment which require, depending on the situation: only CM, MM, RCM\(_a\) (analytical justified reliability centred maintenance) or RCM\(_d\) (reliability centred maintenance, the support being the technical diagnosis).

2. RCM’s applications to power transformers in PS

Maintenance management, in fuzzy mode, requires the definition of the magnitudes for \((k,e,s)\) and estimation of the values \((p\) and \(a\)). In the foregoing reference will be made to power transformers (PT) that have, in PS, the following functions:

- \(f_1\) – self protection
- \(f_2\) – galvanic insulation and separation
- \(f_3\) – transited power energy quality conservation
- \(f_4\) – stressed charge transit in duration regime

In table 1 and 2 are presented the magnitudes for \((k,e,s)\) and their meaning. The magnitude of \(k\) is estimated from two points of view: for the existing transformer (intrinsic) and for the supplied consumer (extrinsic).
TABLE 2 – Efficiency (e) and simplicity (s) scale

<table>
<thead>
<tr>
<th>Level</th>
<th>Significance (e/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = low</td>
<td>Requires corroboration of the results from at least four probes in order to assess the failing (e)</td>
</tr>
<tr>
<td></td>
<td>Requires special analysis, additional tests, professional devices, high costs (s)</td>
</tr>
<tr>
<td>2 = medium</td>
<td>Requires three tests for diagnostic (e)</td>
</tr>
<tr>
<td></td>
<td>Requires withdrawal from the exploitation and special analysis (s)</td>
</tr>
<tr>
<td>3 = good</td>
<td>Requires two tests for diagnostic (e)</td>
</tr>
<tr>
<td></td>
<td>It is not necessary withdrawal from exploitation nor special analysis, but requires adequate devices (s)</td>
</tr>
<tr>
<td>4 = very good</td>
<td>The diagnostic of the failing is made by analysis of the test results</td>
</tr>
<tr>
<td></td>
<td>Simple maintenance operation which requires a minimal support</td>
</tr>
</tbody>
</table>

Referring to frequency, a four-step scale will be employed:

1 = rare \( \equiv \) under 0.1 events / year
2 = less frequent \( \equiv [0.1 \div 1] \) events / year
3 = frequent \( \equiv [1 \div 5] \) events / year
4 = very frequent \( \equiv \) more than \( [5 \div 10] \) events/year

Also, for the magnitudes of synthetic vector \((p,a)\) is suggested to operate with four levels, as defined in table 3.

TABLE 3 – Definition of the levels of the synthetics indicators (p,a)

<table>
<thead>
<tr>
<th>( l_p \times k \times f ) vector</th>
<th>( a )</th>
<th>( e \times s ) vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1 ) = reduced ( (1,1); (1,2); (1,3); (2,1); (2,2); (3,1) )</td>
<td>( 1 ) = low ( (1,1); (1,2); (2,1); (2,2); (3,1) )</td>
<td></td>
</tr>
<tr>
<td>( 2 ) = medium ( (1,4); (2,3); (3,2); (2,4) )</td>
<td>( 2 ) = medium ( (1,3); (1,4); (3,2) )</td>
<td></td>
</tr>
<tr>
<td>( 3 ) = high ( (4,1); (4,2); (3,3) )</td>
<td>( 3 ) = high ( (2,3); (2,4); (4,2); (3,3) )</td>
<td></td>
</tr>
<tr>
<td>( 4 ) = very high ( (3,4); (4,3); (4,4) )</td>
<td>( 4 ) = very high ( (3,4); (4,3); (4,4) )</td>
<td></td>
</tr>
</tbody>
</table>

An essential application path for RCM aims to establish by technical diagnosis (TD) the PT status. Referring to PT, nowadays are used a several TD systems, (methods + detector + equipment + software), which can be characterised with the indicator “a” in according to table 4.

TABLE 4 – TD systems used by PT

<table>
<thead>
<tr>
<th>Diagnose system</th>
<th>“a” indicator’s level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring dissolved gases in oil (7 gases, 4 ratios)</td>
<td>( (3,2) = 2 )</td>
</tr>
<tr>
<td>Monitoring partial discharges</td>
<td>( (3,1) = 2 )</td>
</tr>
<tr>
<td>Measurement of (R,L,C) parameters and of power losses</td>
<td>( (2,2) = 1 )</td>
</tr>
<tr>
<td>Assessment of transfer function ( f ) of PT</td>
<td>( (3,2) = 2 )</td>
</tr>
<tr>
<td>Analysis of frequency response</td>
<td>( (3,2) = 2 )</td>
</tr>
<tr>
<td>Monitoring by on-line and off-line methods (concentration dissolved gases in oil + frequency response)</td>
<td>( (3,3) = 3 )</td>
</tr>
<tr>
<td>Monitoring of PT status parameters (currents, voltages, frequency, temperatures, oil level and pressure, concentration of gases and water in oil, cooling system, and Buchholz relay) and comparison with indent.</td>
<td>( (2,3) = 3 )</td>
</tr>
</tbody>
</table>

The value of the “a” indicator is only one among the global information regarding the potential of a technical diagnosis system (DS). Decisions regarding RCM\(_a\), for \( k = 1,3 \), is mainly justified, grounds by assessment of feasibility indicators:

- Actual net profit (VNA):

\[
VNA = \sum_{t=1}^{T_s} \frac{H_t - G_t}{(1 + R)^t} > 0
\]

- Investment recovery time (DR):

\[
DR = \frac{\frac{1}{a}}{\Delta C + \Delta D - \Delta C_{SD}} \leq \frac{1}{a}
\]

- Profitable indexes (IP)

\[
IP = \frac{\sum_{t=1}^{T_s} H_t (1 + R)^{-t}}{\sum_{t=1}^{T_s} G_t (1 + R)^{-t}} > 1
\]

The economic effort (G) and the economic effect (H), for study period \( (T_s) \) and for year \( (t) \) are computed with the following relations:
where:

\[ I_1 \text{ – investment cost (acquisition + implementation) for the first year when DS is installed;} \]
\[ \Delta C_t \text{ – reduction of costs of PE suppliers in year “} t \text{”, by the existence of DS, in comparison with its absence;} \]
\[ \Delta D_t \text{ – reduction of the (economic, social) consequences of PE consumers;} \]
\[ C_{et}^{SD} \text{ - exploitation costs with DS;} \]
\[ a \text{ – rate of return } [a \in (0.08 \div 0.1)]. \]

The method of calculation of \( C_{et}^{SD}, \Delta C_t, \Delta D_t \) magnitudes can be seen in [4]. The magnitudes of \( (\Delta C, \Delta D, C_{et}^{SD}) \) are average multiannual values of \( C_{et}^{SD}, \Delta C_t, \Delta D_t \). For a PT in operation it will be taken \( T_s = T_r \) (the remaining life-time).

Knowing that the financial sources are limited, the DS installation sequence in PT will be in relation to variation of the series of the value of “IP” indicator.

3. Case study results

The PS from Bihor (PSB) is part of the National Power System (NPS) in Romania. This system consists of many subsystems, which produce, transport, and supply the power energy (PE).

The power energy consumption is over 950 MWh per year, 22% being household consumers.

TABLE 5 – Value of maintenance management indicators for PT from PS of 110 kV/ MV – PS Bihor

<table>
<thead>
<tr>
<th>Nr.</th>
<th>PS name</th>
<th>PT characterize</th>
<th>( \gamma )</th>
<th>( k_i )</th>
<th>( k_i )</th>
<th>( k_i )</th>
<th>Fuzzy level</th>
<th>Maintenance strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>Aleşd</td>
<td>16 MVA 110/20 kV</td>
<td>1,39</td>
<td>0,27</td>
<td>0,54</td>
<td>0,1</td>
<td>1</td>
<td>CM</td>
</tr>
<tr>
<td>2</td>
<td>Bălăta</td>
<td>(16+10)MVA 110/6 kV</td>
<td>0,73</td>
<td>0,04</td>
<td>0,13</td>
<td>0,05</td>
<td>1</td>
<td>CM</td>
</tr>
<tr>
<td>3</td>
<td>Beiuş</td>
<td>(25+16)MVA 110/20 kV</td>
<td>1,87</td>
<td>0,996</td>
<td>0,992</td>
<td>0,24</td>
<td>2</td>
<td>MM</td>
</tr>
<tr>
<td>4</td>
<td>CLA Aleşd</td>
<td>4x40 MVA 110/6 kV</td>
<td>11,81</td>
<td>1,35</td>
<td>1,65</td>
<td>4,37</td>
<td>3</td>
<td>RCMd</td>
</tr>
<tr>
<td>5</td>
<td>Crişul</td>
<td>25 MVA 110/6 kV</td>
<td>19,55</td>
<td>2,12</td>
<td>2,37</td>
<td>2,55</td>
<td>3</td>
<td>RCMd</td>
</tr>
<tr>
<td>6</td>
<td>Ioaia</td>
<td>25 MVA 110/20 kV</td>
<td>1,92</td>
<td>0,86</td>
<td>1,13</td>
<td>0,25</td>
<td>2</td>
<td>MM</td>
</tr>
<tr>
<td>7</td>
<td>Oradea Centru</td>
<td>2x25 MVA 110/20 kV</td>
<td>28,4</td>
<td>3,47</td>
<td>2,43</td>
<td>3,44</td>
<td>3</td>
<td>RCMd</td>
</tr>
<tr>
<td>8</td>
<td>Oradea Nord</td>
<td>(25+10)MVA 110/20 kV</td>
<td>10,95</td>
<td>1,77</td>
<td>1,42</td>
<td>0,79</td>
<td>3</td>
<td>RCMd</td>
</tr>
<tr>
<td>9</td>
<td>Palota</td>
<td>(25+10)MVA 110/20 kV</td>
<td>12,21</td>
<td>0,62</td>
<td>0,44</td>
<td>1,59</td>
<td>2</td>
<td>MM</td>
</tr>
<tr>
<td>10</td>
<td>Salonta</td>
<td>(25+16)MVA 110/20 kV</td>
<td>11,87</td>
<td>1,99</td>
<td>1,48</td>
<td>1,55</td>
<td>3</td>
<td>RCMd</td>
</tr>
<tr>
<td>11</td>
<td>Sâcueni</td>
<td>2x16 MVA 110/20 kV</td>
<td>9,14</td>
<td>0,95</td>
<td>0,95</td>
<td>0,66</td>
<td>2</td>
<td>MM</td>
</tr>
<tr>
<td>12</td>
<td>Sinteza</td>
<td>16 MVA</td>
<td>22,78</td>
<td>1,99</td>
<td>1,94</td>
<td>1,65</td>
<td>3</td>
<td>RCMd</td>
</tr>
</tbody>
</table>

Since 1990, the Department of Distribution, Supply of Power Energy Bihor which manages PS in Bihor, power transportation, distribution and supply subsystems, instituted a new method to carry out the operational reliability studies, whose characteristics and results were the topics of several published papers [3,4,10].

Forty PT belonging to the 20 PS of 110 kV/MV were also the targeted in operational reliability studies. Hierarchisation of elements by the impact of failing of PT [4], shows that wire failing represents 74% of PT breakdown cases. The statistical analysis regarding the behaviour of PT in exploitation, was carried out with respect to random variables (VA), time between failures (TBF) and time of corrective maintenance (TMC), being tested the exponential, Weibull and normal distribution laws. The results show that the law which best describes with minimum errors the statistic values is the law of Weibull [4]. For operative estimates exponential distribution with \( \lambda = 8.56 \times 10^{-5} \text{ h}^{-1} \) and \( \mu = 0.063 \text{ h}^{-1} \) parameters may be used.

For parameters of distribution of random parameter TBF are obtained 0.75 events/year, corresponding to \( f = 2 \). For the maintenance management of the 40 PT belonging to PS Bihor were estimated the \( \gamma \) and \( k \) indicators (table 5). Regarding the “\( k \)” indicator, three relative values were estimated \((k_1, k_2, k_3)\) with the following significance:

- \( k_1 \) – absolute social consequences / medium absolute social consequences;
- \( k_2 \) – economic consequences at supplier side / average economic consequences at supplier side;
- \( k_3 \) – economic consequences at consumer side/ average economic consequences by consumers.
Based on three values of \((k_1, k_2, k_3)\) the PT from PS was framed in one of the 4 fuzzy levels and suggested the adequate maintenance strategy. Level “4” consequences are not occurring, because the potential consumers of this type have their own sources for supplying the receivers in question. For the PT-s for which is recommended the application of MM strategy, by applying a mathematic model of optimisation of total cost of maintenance works \([3,4,10]\), has been determined the time between 2 successive interventions (1.5 year) and probable average duration of the maintenance works (16 hours) respectively.

4. Conclusions

Maintenance is the second most important lever (together with the quality of equipment) through which the equipment and system availability level is influenced. For electric equipment maintenance strategy evolved through the last 5 decades, nowadays being well structured and hierarchised.

Reliability centred maintenance is a good example for scientific management of maintenance, founded on studies of operational reliability and technical subsystems diagnosis.

Reliability centred maintenance is applied in correlation with other processes of reengineering, having as scope of improving the performance of processes.

Application of TBF referring to power equipment, in principle involves: the equipment hierarchisation in accordance with economic importance, FMEA studies, assessment of certain levels for indicators which determine dangerous failings and applicability of different maintenance strategies, set-up of maintenance staff.

The application of maintenance management methodology for power transformers (110 kV/MV) allows their hierarchisation according to the parameters \(k\) and \(\gamma\), and therefore assess, the adequate maintenance strategy (RCM\(d\), MM, CM). For PT for which is recommended the RCM\(d\) strategy, was introduced a system based on analysis of gases contained in the oil. According to the evaluated indicators, is recommended to transfer a PT from Suplac PS (110/6 kV) to Stei PS. The PS hierarchisation where MM is practised in case of overlapping of undesirable events and restrictions (financial, material, manpower) is made as follows: 15-9-11-14-6-3.

References

[10] I. Stoica, N. Coroiu., I. Felea, 2000, Contributions to the switchinggear maintenance, optimization in a local electric power system, Session CIGRE.