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Optimal spares availability strategy for power transformer components

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ABSTRACT

The paper suggests a method to optimize the spare amount of power transformer components. The proposed strategy is conceived to provide minimum annual cost consisting of expected failures renewal cost, capital cost for spares and load curtailment cost. The method identifies minor and major failures. Minor failures are repairable, while major failures can be repairable or unrepairable. Power transformer is a complex system, consisting of six components (functional parts). It is assumed that each component has two independent, competing failure modes: wear-out failure mode, modelled by two-parameter Weibull distribution, and a chance failure mode, characterized by an exponential distribution. The application of the method suggested and the benefits it provides are demonstrated for one transformer station (TS) 110/x kV/kV with 2×31.5 MVA transformers. In addition, the influence of performing power transformer refurbishment on expected total cost has also been analyzed.

1. Introduction

Equipment failures in distribution substations may cause interruptions in the power supply, which leads to power distribution company and customer costs. The customer costs depend on the consumer types and generally increase with the duration of the supply interruption. Power distribution company cost is in proportion to the degree of damages and the energy which has not been delivered to the customer [1,2]. The most severe consequences arise after power transformer failures, because the time for renewal of a damaged transformer can be very long and renewal process can be expensive.

Failures of power transformer are classified as repairable or unrepairable. Renewal time of repairable failures usually is not long and spare parts are not necessary. Unrepairable failures request using of spare parts, so renewal time depends of necessary spare parts availability. Purchase of spare parts will substantially reduce unrepairable failures renewal time, but it implies considerable investment cost. Whether purchasing of spare parts is justified or not can be established by performing cost/benefit analysis.

As it is known, failure rate is increasing with aging of equipment, Fig. 1 [3]. In this paper, it is adopted that exploitation period for power transformers is about 40 years. Fig. 1 inferrs that during the first several years the failure rate is very low, so it is quite reasonable assumption that purchasing of spare power transformer is not necessary. With the help of precise statistical data, it is possible, during determination of optimal number of spare parts, to consider purchasing only some components, not entire power transformer.

A model which enables determination of optimal spare amount of power transformer components is formulated for the following cases:

– performing of transformer refurbishment is not planned during exploitation period and
– transformer refurbishment will be performed at the optimal point of time. Performing of refurbishment at the optimal point of time provides minimum load curtailment cost.

The application of the model suggested in the paper is demonstrated for one transformer station (TS) 110/x kV/kV with 2×31.5 MVA transformers.

2. Basic assumptions

At any point of time, the status of power transformer can be classified as either operating or failed. Failed status is a result of minor failures and/or major failures. Minor failures are repairable and can be repaired for $t \le 24$ h. Major failures can be repairable or unrepairable.

Hence, probability that the component "k" of power transformer is in operating status equals

$$R_k(t) = \exp(-(\lambda_{k,\mathrm{mf}} + \lambda_{k,\mathrm{MF}})t) \exp\left(-\left(\frac{t}{\alpha_k}\right)^{\beta_k}\right) \quad (1)$$

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Table 1
Power transformer components reliability data [4].

k		p_k (%)	Failure class i	$p_{k,I}$ (%)	$r'_{k,i}$ (day)	$r''_{k,i}$ (day)
1	Windings	26.4	2	14.54	30	15
			3	85.46	250	15
2	Bushings	12	1	14.82	1	1
			2	51.85	40	3
			3	33.33	40	15
3	Tank	7.9	1	58.82	1	1
			2	23.53	3	3
			3	17.65	90	15
4	On-load tap-changer	40.7	1	25.61	1	1
			2	52.44	3	3
			3	21.95	40	3
5	Other accessories	10.6	1	65.22	1	1
			2	17.39	15	15
			3	17.39	40	15
6	Core	2.4	2	50	30	15
			3	50	180	15

i.e. we assume that the component has two independent failure modes: a chance failure mode, characterized by the exponential distribution, and a wear-out mode, modelled by two-parameter Weibull distribution.

Power transformer consists of six components-functional parts [4]: (1) windings + oil, (2) bushings, (3) tank, (4) on-load tap-changer, (5) other accessories, (6) core.

With regard to the failure repair time, there are three failure classes [4,6,7]:

(i = 1) failures which can be repaired for $t \leq 1$ day;
(i = 2) failures which can be repaired for 1 day < t < 30 days;
(i = 3) failures which can be repaired for $t \geq 30$ days.

Failures from the class (i = 1) are repairable.
Failures from the class (i = 2) are:

- repairable major failures for tank, on-load tap-changer and other accessories (failure renewal cost does not depend of spare component availability);
- unrepairable major failures for Windings, Bushings and Core (failure renewal cost depends of spare component availability).

Failures from the class (i = 3) are unrepairable major failures.

Relevant data for power transformer components (p_k, $p_{k,i}$, $r'_{k,i}$, $r''_{k,i}$) are presented in Table 1 [4].

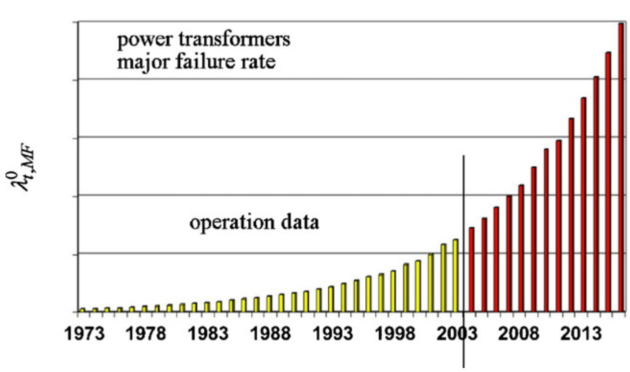

Fig. 1. Statistical data about major failure rate $\lambda^0_{t,\mathrm{MF}}$ during time interval (1973–2003) [3].

3. Model development

In the case of exploitation without keeping of spare components and without performing of refurbishment, total cost during the planning period consists of expected failures renewal cost and load curtailment cost. Average yearly cost per transformer during time interval (t, t + 1), (t = 1,N − 1) equals [5,6]

$$C_{\mathrm{ET,\,no\ s.p.}}(t,\ t+1)=\frac{[R_{\mathrm{tot}}(t)-R_{\mathrm{tot}}(t+1)]\sum_{k=1}^{b}p_k\left(\sum_{i=1}^{f_k}p_{k,i}C'_{k,i}\right)}{D_{\mathrm{no\,s.p.}}(t,\ t+1)}$$
$$R_{\mathrm{tot}}(t)=\prod_{k=1}^{b}R_k(t) \tag{2}$$
$$D_{\mathrm{no\,s.p.}}(t,\ t+1)=\int_t^{t+1}R_{\mathrm{tot}}(t)\,\mathrm{d}t+[R_{\mathrm{tot}}(t)-R_{\mathrm{tot}}(t+1)]\sum_{k=1}^{b}p_k\sum_{i=1}^{f_k}p_{k,i}r'_{k,i}$$

The numerator in (2) is the expected cost of failures renewal during time interval (t, t + 1) without keeping of spare components. The first term in $D_{\mathrm{no\,s.p.}}(t, t+1)$ is the mean time to failure, second-expected time of failures renewal during time interval (t, t + 1).

An average yearly unavailability of transformer during time interval (t, t + 1) equals

$$U_{\mathrm{ET,\,no\ s.p.}}(t,\ t+1)=\frac{[R_{\mathrm{tot}}(t)-R_{\mathrm{tot}}(t+1)]\sum_{k=1}^{b}p_k\left(\sum_{i=1}^{f_k}p_{k,i}r'_{k,i}\right)}{D_{\mathrm{no\,s.p.}}(t,\ t+1)} \tag{3}$$

An average yearly down-time of one transformer and of both transformers during time interval (t, t + 1) are respectively [6]:

$$\tau_{1,\mathrm{\ no\ s.p.}}(t,\ t+1)=U_{\mathrm{ET,\,no\ s.p.}}(t,\ t+1)8760\,[\mathrm{h}]$$
$$\tau_{2,\mathrm{\ no\ s.p.}}(t,\ t+1)=U_{\mathrm{ET,\,no\ s.p.}}(t,\ t+1)^2 8760\,[\mathrm{h}] \tag{4}$$

Investing capital in spare components increases total cost but it leads to the power transformer unavailability reduction, i.e. reduction of failures renewal cost and load curtailment cost. According to the proposed strategy, purchasing of spare part, say, "j" is performed after T_j years of continuing operation without failure. If transformer component "j" fails prior to T_j, repair is performed at the time of the failure, otherwise spare component "j" will be purchased. The influence of spare component "j" stored at the beginning of year T_j on average yearly cost and average yearly unavailability of transformer during time interval (t, t + 1), $t \geq T_j$,can

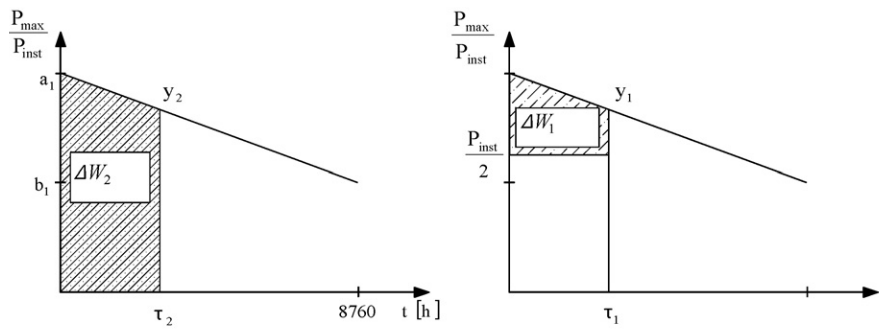

Fig. 2. Annual hourly load-duration diagram ($a_1 = 0.8$, $b_1 = 0.4$).

be included as follows

$$C_{\text{ET, s.p.}}(t, t+1) = \frac{[R_{\text{tot}}(t) - R_{\text{tot}}(t+1)]\left(p_j \sum_{i=1}^{f_j} p_{j,i} C''_{j,i} + \sum_{\substack{k=1 \\ k \neq j}}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} C'_{k,i}\right)}{D_{\text{s.p.}}(t, t+1)} + \frac{R_{\text{tot}}(T_j) C_{\text{new},j}}{\int_0^N R_{\text{tot}}(t)\,dt + U_{\text{I}}(0, N)} \tag{5}$$

$$U_{\text{ET, s.p.}}(t, t+1) = \frac{[R_{\text{tot}}(t) - R_{\text{tot}}(t+1)]\left(p_j \sum_{i=1}^{f_j} p_{j,i} r''_{j,i} + \sum_{\substack{k=1 \\ k \neq j}}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i}\right)}{D_{\text{s.p.}}(t, t+1)} \tag{6}$$

expected yearly failures renewal cost, load curtailment cost and investment cost are: $2C_{\text{ET, s.p.}}(t, t+1) + \Delta W_{\text{TS, s.p.}}(t, t+1) C_{\text{EN}} + \frac{R_{\text{tot}}(T_j) C_{\text{new},j}}{\int_0^N R_{\text{tot}}(t)\,dt + U_{\text{I}}(0,N)}$. Purchasing of spare component "j" at the beginning of the year T_j is justified if:

$$\frac{R_{\text{tot}}(T_j) C_{\text{new},j}}{\int_0^N R_{\text{tot}}(t)\,dt + U_{\text{I}}(0, N)} \leq 2(C_{\text{ET, no s.p.}}(t, t+1) - C_{\text{ET, s.p.}}(t, t+1)) + C_{\text{EN}}(\Delta W_{\text{TS, no s.p.}}(t, t+1) - \Delta W_{\text{TS, s.p.}}(t, t+1)) \tag{9}$$

Another measure for the improvement of power transformer reliability which will be considered here is refurbishment. By performing of refurbishment one exploitation cycle is finished and another starts. After refurbishment the transformer will be "as good as new". Performing of refurbishment at the optimal point of time T_{ref} provides minimum load curtailment cost, i.e.:

$$U_{\text{ET}}(0, T_{\text{ref}}) = \frac{(1 - R_{\text{tot}}(T_{\text{ref}}))\sum_{k=1}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i} + R_{\text{tot}}(T_{\text{ref}}) t_{\text{ref}}}{\int_0^{T_{\text{ref}}} R_{\text{tot}}(t)\,dt + (1 - R_{\text{tot}}(T_{\text{ref}}))\sum_{k=1}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i} + R_{\text{tot}}(T_{\text{ref}}) t_{\text{ref}}} \rightarrow \min \tag{10}$$

$$U_{\text{I}}(0, N) = [1 - R_{\text{tot}}(T_j)] \sum_{k=1}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i} + [R_{\text{tot}}(T_j) - R_{\text{tot}}(N)] \left(p_j \sum_{i=1}^{f_j} p_{j,i} r''_{j,i} + \sum_{\substack{k=1 \\ k \neq j}}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i}\right)$$
$$D_{\text{s.p.}}(t, t+1) = \int_t^{t+1} R_{\text{tot}}(t)\,dt + [R_{\text{tot}}(t) - R_{\text{tot}}(t+1)] \left(p_j \sum_{i=1}^{f_j} p_{j,i} r''_{j,i} + \sum_{\substack{k=1 \\ k \neq j}}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i}\right) \tag{7}$$

In Eq. (5), the first term is the expected failure renewal cost during time interval (t, $t+1$) if spare component "j" is available, second term is average yearly investment cost for spare component "j".

With available spare component "j", an average yearly downtime of one transformer and of both transformers during time interval (t, $t+1$) are respectively:

$$\begin{aligned} \tau_{1,\text{ s.p.}}(t, t+1) &= U_{\text{ET, s.p.}}(t, t+1) 8760\,[\text{h}] \\ \tau_{2,\text{ s.p.}}(t, t+1) &= U_{\text{ET, no s.p.}}(t, t+1) U_{\text{ET, s.p.}}(t, t+1) 8760\,[\text{h}] \end{aligned} \tag{8}$$

Whether the purchasing of spare component "j" at the beginning of the year T_j is justified can be confirmed as follows: if spare components are not stored, for transformer station with two installed units, expected yearly failures renewal cost and load curtailment cost are: $2C_{\text{ET, no s.p.}}(t, t+1) + \Delta W_{\text{TS, no s.p.}}(t, t+1) C_{\text{EN}}$. If spare component "$j$" is available from the beginning of the year T_j,

Average yearly cost during one exploitation cycle, without keeping of spare components, is [5,6]:

$$C_{\text{ET}}(0, T_{\text{ref}}) = \frac{(1 - R_{\text{tot}}(T_{\text{ref}})) \sum_{k=1}^{b} p_k \left(\sum_{i=1}^{f_k} p_{k,i} C'_{k,i}\right) + R_{\text{tot}}(T_{\text{ref}}) C_{\text{ref}}(T_{\text{ref}})}{\int_0^{T_{\text{ref}}} R_{\text{tot}}(t)\,dt + (1 - R_{\text{tot}}(T_{\text{ref}})) \sum_{k=1}^{b} p_k \sum_{i=1}^{f_k} p_{k,i} r'_{k,i} + R_{\text{tot}}(T_{\text{ref}}) t_{\text{ref}}} \tag{11}$$

4. Application

An application of the model will be demonstrated for one TS 110/x kV/kV, with two power transformers installed, $P_{\text{inst}} = 2 \times 31.5$ MVA = 63 MVA.

Table 2
Power transformer components costs [4].

k	Transformer component	$C_{\mathrm{new},k}$ (EUR)
1	Windings	250 000
2	Bushing	800
3	Tank	28 000
4	On-load tap-changer	42 000
5	Other accessories	22 000
6	Core	80 000

Table 4
Weibull distribution parameters.

k	Component	β_k	α_k
1	Windings	3.58	57.0131
2	Bushings	3.58	74.3159
3	Tank	3.58	102.321
4	On-load tap-changer	3.58	54.8723
5	Other accessories	3.58	98.8079
6	Core	3.58	111.395

Calculations are made for planning period of $N = 40$ years.

The annual hourly load-duration diagram for the substation is displayed in Fig. 2. Peak load is 80% and minimum load is 40%, with regard to the installed capacity. It is assumed that the load has reached its saturation and that there are no annual load level increments during the planning period.

Calculations are made under assumption that failures occur during the peak load period, which is the most critical case.

With regard to Fig. 2, (4) and (8), for energy not delivered we have:

$$y_{1(2)} = \left[a_1 - \frac{a_1 - b_1}{8760}\tau_{1(2)}(t, t+1)\right] P_{\mathrm{inst}} \tag{12}$$

$$\begin{aligned} \Delta W_1 &= 2\frac{a_1 P_{\mathrm{inst}} - 0.5P_{\mathrm{inst}} + y_1 - 0.5P_{\mathrm{inst}}}{2}\tau_1(t, t+1) = (y_1 + a_1 P_{\mathrm{inst}} - P_{\mathrm{inst}})\tau_1(t, t+1) \\ \Delta W_2 &= \frac{a_1 P_{\mathrm{inst}} + y_2}{2}\tau_2(t, t+1) \end{aligned} \tag{13}$$

Average yearly energy not delivered equals

$$\Delta W_{\mathrm{TS}}(t, t+1) = C_{\mathrm{EN}}[\Delta W_1 + \Delta W_2]\,[\mathrm{EUR/year}] \tag{14}$$

The loss of revenue and load curtailment cost per kWh not delivered is $C_{\mathrm{EN}} = 0.10$ EUR/kWh (average electricity price for medium size households in EU).

Purchase cost of new oil is $C_{\mathrm{new,\,oil}} = 40\,000$ EUR. Cost of oil filtration and drying is $C_{\mathrm{u}} = 0.2C_{\mathrm{new,\,oil}}$.

The duration of refurbishment performing is $t_{\mathrm{ref}} = 28$ days.

Relevant data for power transformer components are presented in Tables 2 and 3 [4].

Parameters in (1) are determined, based on Fig. 2 [3,7], by applying the least-squares method.

It is adopted that average failure rate of power transformer during 30 years of exploitation is $\lambda = 0.015$/year [4,8].

For combination of exponential and Weibull distribution, major failure rate equals

$$\lambda_{\mathrm{MF}}(t) = \lambda^0_{0,\mathrm{MF}} + \frac{\beta}{\alpha^\beta}t^{\beta-1} \tag{15}$$

Applying the least-squares method, parameters of Weibull distribution are determined as solutions of the Eqs. (17) and (18):

$$\varepsilon(\alpha, \beta) = \sum_{t=1}^{30}(\lambda_{\mathrm{MF}}(t) - \lambda^0_{t,\mathrm{MF}})^2 \tag{16}$$

$$\frac{\partial \varepsilon(\alpha, \beta)}{\partial \alpha} = 0 \tag{17}$$

$$\frac{\partial \varepsilon(\alpha, \beta)}{\partial \beta} = 0 \tag{18}$$

The partial derivative with respect to β (18) is not practically usable because of complexity. For precise modelling of curve from Fig. 1 with (15), following procedure is performed: for $\beta_k > 1$, with step of 0.01, values of α_k, with regards to Table 1, are calculated. For $\alpha_k i \beta_k$ we adopted those values for which Eq. (16) has minimum, Table 4. Also, it is valid:

$$\sum_{k=1}^{6}(\lambda_{k,\mathrm{MF}} + \lambda_{k,\mathrm{mf}}) + \frac{1}{30}\sum_{t=1}^{30}\sum_{k=1}^{6}\left(\frac{\beta_k}{\alpha_k^{\beta_k}}t^{\beta_k-1} - \frac{\beta_k}{\alpha_k^{\beta_k}}(t-1)^{\beta_k-1}\right) \approx \lambda_{\mathrm{av}} \tag{19}$$

Table 3
Costs of failures renewal on power transformer components [4].

k		p_k (%)	failure class i	$p_{k,i}$ (%)	$C'_{k,i}$	$C''_{k,i}$,
1	Windings	26.4	2	14.54	$0.2C_{\mathrm{new},1} + C_{\mathrm{u}}$	C_{u}
			3	85.46	$0.5C_{\mathrm{new},1} + C_{\mathrm{u}}$	C_{u}
2	Bushings	12	1	14.82	$0.4C_{\mathrm{new},2}$	$0.4C_{\mathrm{new},2}$
			2	51.85	$C_{\mathrm{new},2}$	–
			3	33.33	$C_{\mathrm{new},2} + C_{\mathrm{u}}$	C_{u}
3	Tank	7.9	1	58.82	$0.1C_{\mathrm{new},3}$	$0.1C_{\mathrm{new},3}$
			2	23.53	$0.2C_{\mathrm{new},3}$	$0.2C_{\mathrm{new},3}$
			3	17.65	$C_{\mathrm{new},3} + C_{\mathrm{u}}$	C_{u}
4	On-load tap-changer	40.7	1	25.61	$0.1C_{\mathrm{new},4}$	$0.1C_{\mathrm{new},4}$
			2	52.44	$0.2C_{\mathrm{new},4}$	$0.2C_{\mathrm{new},4}$
			3	21.95	$0.4C_{\mathrm{new},4}$	–
5	Other accessories	10.6	1	65.22	$0.1C_{\mathrm{new},5}$	$0.1C_{\mathrm{new},5}$
			2	17.39	$0.5C_{\mathrm{new},5}$	$0.5C_{\mathrm{new},5}$
			3	17.39	$C_{\mathrm{new},5}$	–
6	Core	2.4	2	50	$0.2C_{\mathrm{new},6} + C_{\mathrm{u}}$	C_{u}
			3	50	$0.5C_{\mathrm{new},6} + C_{\mathrm{u}}$	C_{u}

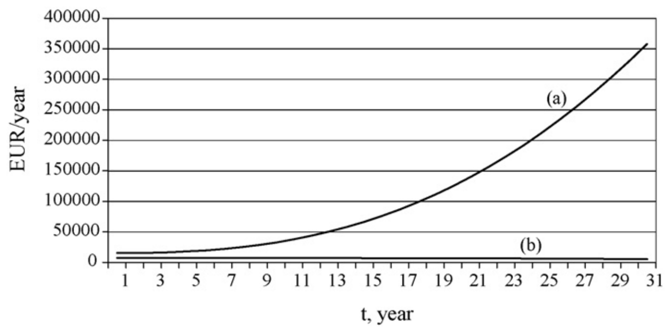

Fig. 3. Reduction of failures renewal cost and load curtailment cost if spare windings are available (curve a) and annual capital cost for different years of spare windings purchasing (curve b).

In the case of exploitation without performing refurbishment for planning period of $N = 40$ years, the results of the analysis are as it follows:

4.1. Radial supplying of customers

– Purchasing of spare windings is justified from the first year of exploitation. The yearly investment cost for spare windings is 7494.55 EUR/year. The reduction of failures renewal cost and load curtailment cost during the first year is 15 492.1 EUR/year. Fig. 3 shows the reduction of failures renewal cost and load curtailment cost (curve a) and annual capital cost for different years of purchasing of spare windings (curve b).
– Purchasing of spare bushings is justified, also, from the first year of exploitation. The yearly investment cost for spare bushings is 143.67 EUR/year. The reduction of failures renewal cost and load curtailment cost during the first year is 5753.15 EUR/year.
– Purchasing of the spare on-load tap-changer is justified from the seventh year of exploitation. The yearly investment cost for spare on-load tap-changer is 1242.96 EUR/year. The reduction of failures renewal cost and load curtailment cost during the seventh year is 1365.12 EUR/year. Fig. 4 shows the reduction of failures renewal cost and load curtailment cost (curve a) and annual capital cost for different years of purchasing of spare on-load tap-changer (curve b).
– Purchasing of the spare tank is justified from the twelfth year of exploitation. The yearly investment cost for spare tank is 816.15 EUR/year. The reduction of failures renewal cost and load curtailment cost during the twelfth year is 848.67 EUR/year.
– Purchasing of the spare other accessories is justified from the thirteenth year of exploitation. The yearly investment cost for spare other accessories is 638.36 EUR/year. The reduction of failures renewal cost and load curtailment cost during the thirteenth year is 686.84 EUR/year.

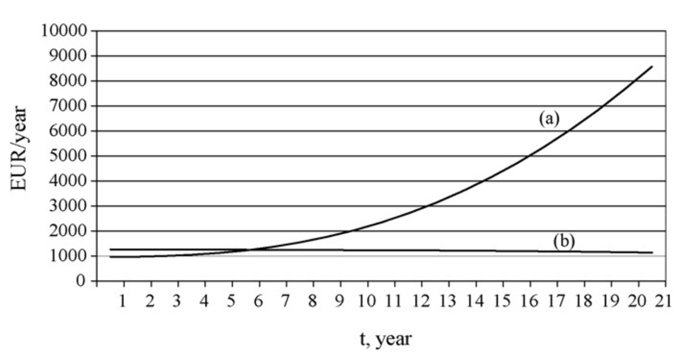

Fig. 4. Reduction of failures renewal cost and load curtailment cost if spare on-load tap-changer is available (curve a) and annual capital cost for different years of spare windings purchasing (curve b).

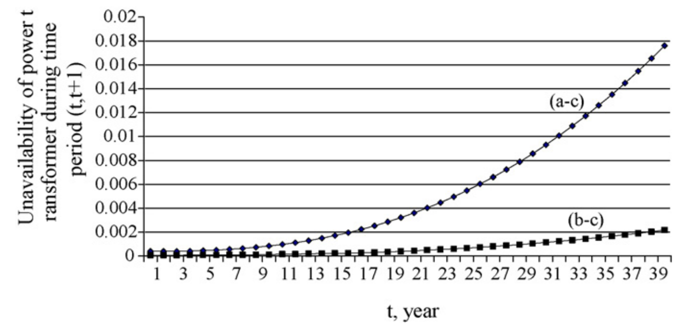

Fig. 5. A comparative overview of transformer unavailability for the case of operation without keeping of spare components (curve a–c) and the case when optimal amount of spare components is available (curve b–c).

– Purchasing of the spare core is justified from the fifteenth year of exploitation. The yearly investment cost for spare core is 2295.52 EUR/year. The reduction of failures renewal cost and load curtailment cost during the fifteenth year is 2455.08 EUR/year.

Concerning the above mentioned, it can be concluded that the optimal solution is:

– Storing of spare windings and bushings from the beginning of the first year.
– Storing of spare on-load tap-changer from the beginning of the seventh year.
– Storing of spare tank from the twelfth year.
– Storing of spare other accessories from the thirteenth year.
– Storing of spare core from the fifteenth year.

Fig. 5 shows a comparative overview of transformer unavailability for the case of operation without keeping of spare components (curve a–c) and the case when optimal amount of spare components is available (curve b–c).

4.2. Outage of one power transformer does not affect the customers supplying

Storing of any spare component is not justified.

4.3. Performing of power transformer refurbishment

Owners of TS from Europe, the USA and Japan have reported that they perform power transformer refurbishment after 25–30 years of exploitation, which costs $(0.4–0.5)C_{\text{new}}$. If we assume that this cost is linearly proportional to the period of exploitation prior to the refurbishment, we can calculate that the "yearly cost of refurbishment" is $(0.013–0.025)C_{\text{new}}$/year.

Minimal unavailability, Eq. (10), is achieved if refurbishment is performed after 26 years of exploitation, without keeping of spare components. After refurbishment transformer is "as good as new" and can work at least as many years as it had worked before refurbishment.

If optimal amount of spare components is stored refurbishment performing is not justified.

Fig. 6 shows a comparative overview of transformer unavailability for the case of refurbishment performing after 26 years of operation without keeping of spare components (curve c–c) and the case when optimal amount of spare components is available (curve d–c).

It is important to emphasize the following: refurbishment because of the delay purchasing of a new transformer is not eco-

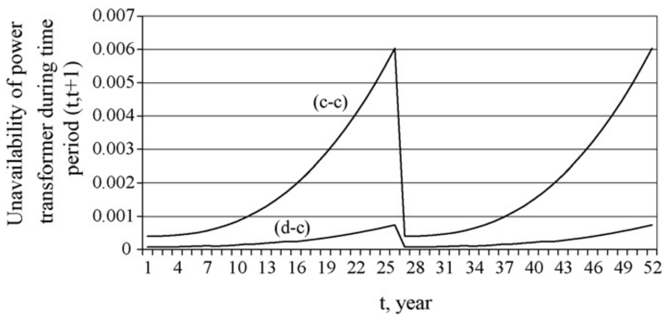

Fig. 6. A comparative overview of transformer unavailability for the case of refurbishment performing after 26 years of operation without keeping of spare components (curve c–c) and the case when optimal amount of spare components is available (curve d–c).

nomically justified. For example, simple calculation is made: the present worth cost of purchasing of a new transformer after 40 years of exploitation (in other words, at the beginning of the new exploitation period), with the net discount rate of, say, 5% per year is: $C_{\text{new}}(1/1.05)^{40} = 0.142C_{\text{new}}$. Similarly, the present worth cost of refurbishment after 26 years of exploitation and of purchasing of a new transformer after 52 years is:

– for upper value of yearly cost of refurbishment

$$\frac{26(0.02C_{\text{new}})}{1.05^{26}} + \frac{C_{\text{new}}}{1.05^{52}} = 0.22534C_{\text{new}},$$

– for lower value of yearly cost of refurbishment $\frac{26(0.013C_{\text{new}})}{1.05^{26}} + \frac{C_{\text{new}}}{1.05^{52}} = 0.17635C_{\text{new}}$.

5. Conclusions

The paper suggests a method for optimizing the amount of spare components for power transformer to provide minimal total cost, comprising load curtailment, failures renewal and storage investment costs during a planning period. In addition, performing of power transformer refurbishment, as a possible way for reduction of load curtailment cost, is analyzed.

The analysis performed in the paper has shown that the application of the proposed optimization method can substantially decrease the total cost.

Owing to the generalization method, further work should encompass sensitivity analysis of impact of the following factors on the spares availability policy for power transformer components and optimal point of time of refurbishment performing:

– ratio r'_{ki}/C^{i}_{ki};
– ratio $t_{\text{ref}}/C_{\text{ref}}(T_{\text{ref}})$; and
– application of condition monitoring system.

Appendix A. List of symbols

TS	transformer station
t	time
C_{new}	purchase cost of new power transformer
$C_{\text{new},k}$	purchase cost of power transformer component "*k*"
$C_{\text{new,oil}}$	purchase cost of new oil
C_{u}	cost of oil filtration and drying
b	number of functional parts-components of power transformer
f_k	number of failure classes of power transformer component "*k*" with regard to the failure repair time
p_k	probability that the failure occurs on power transformer component "*k*" $\left(\sum_{k=1}^{b} p_k = 1\right)$
$p_{k,i}$	probability that the failure of class "*i*" occurs on component "*k*" $\left(\sum_{i=1}^{f_k} p_{k,i} = 1\right)$
$C_{\text{ET}}(t, t+1)$	average yearly cost per transformer during time interval $(t, t+1)$
$C'_{k,i}$	renewal cost of class "*i*" failure on component "*k*" if spare component "*k*" is not available
$C''_{k,i}$	renewal cost of class "*i*" failure on component "*k*" if spare component "*k*" is available
$r'_{k,i}$	renewal time of class "*i*" failure on component "*k*" if spare component "*k*" is not available
$r''_{k,i}$	renewal time of class "*i*" failure on component "*k*" if spare component "*k*" is available
λ_{av}	average failure rate of power transformer
$\lambda_{k,\text{MF}}$	major failure rate of component "*k*"
$\lambda_{k,\text{mf}}$	minor failure rate of component "*k*"
$\lambda^0_{t,\text{MF}}$	initial (statistical) data for major failure rate at time *t*
$\lambda^0_{0,\text{MF}}$	$= \lambda^0_{t,\text{MF}}\vert_{t=0}$
$\lambda^0_{0,\text{mf}}$	initial (statistical) data for minor failure rate at time *t*=0
λ^0_0	$= \lambda^0_{0,\text{MF}} + \lambda^0_{0,\text{mf}}$
β	the Weibull shape parameter
α	the Weibull scale parameter.
$R(t)$	reliability
$U(t)$	unavailability
$\tau_1(t, t+1)$	average yearly down-time of one transformer during time interval $(t, t+1)$
$\tau_2(t, t+1)$	average yearly down-time of both transformers during time interval $(t, t+1)$
$\Delta W_{\text{TS}}(t, t+1)$	average yearly energy not delivered during time interval $(t, t+1)$
ΔW_1	average yearly energy not delivered due to outage of one transformer
ΔW_2	average yearly energy not delivered due to outage of both transformers
C_{EN}	loss of revenue and load curtailment cost per kWh not delivered
N	duration of the planning period, expressed in years
P_{inst}	substation installed capacity
t_{ref}	duration of refurbishment performing
$C_{\text{ref}}(T_{\text{ref}})$	cost of refurbishment performing at the point of time T_{ref}

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