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Operation Modes of HV/MV Substations

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Abstract*- A distribution network consists of high voltage grid, medium voltage grid, and low voltage grid. Medium voltage grid is connected to high voltage grid via substations with HV/MV transformers. The substation may contain one, mostly two but sometimes even more transformers. Out of reliability and expenditure considerations the two transformer option prevail over others mentioned. For two transformer substation, there may be made choice out of several operation modes: 1) two (small) transformers, with rated power each over 0.7 of maximum substation load, permanently in operation; 2) one (big) transformer, with rated power over maximum substation load, permanently in operation and small transformer in constant cold reserve; 3) big transformer in operation in cold season, small transformer – in warm one. Considering transformer load losses and no load losses and observing transformer loading factor β it can be said that the mode 1) is less advantageous. The least power losses has the mode 3). There may be singled out yet three extra modes of two transformer substations: 4) two big transformers in permanent operation; 5) one big transformer permanently in operation and one such transformer in cold reserve; 6) two small transformers in operation in cold season of the year, in warm season – one small transformer on duty. At present mostly two transformers of equal power each are installed on substations and in operation is one of them, hence extra mode 5). When one transformer becomes faulty, it can be changed for smaller one and the third operation mode can be practiced. Extra mode 4) is unpractical in all aspects. The mode 6) has greater losses than the mode 3) and is not considered in detail. To prove the advantage of the third mode in sense of power losses, the notion of effective utilization time of power losses was introduced and it was proven that relative value of this quantity diminishes with loading factor β. The use of advantageous substation option would make it possible to save notable amount of electrical energy but smaller transformer lifetime of this option must be taken into account as well.

***Keywords**: step down substations, transformers, transformer losses*

I. INTRODUCTION

A distribution network consists of high voltage grid, medium voltage grid, and low voltage grid [1]. Medium voltage grid is fed via substations with HV/MV transformers. The substation may contain one, mostly two but sometimes even more transformers. Three transformer option in ordinary conditions is less preferable because of its greater costs and expenses. First and second category consumers demand high reliability of energy delivery and one transformer is not acceptable in such cases [2;3]. The adopted option is substation with two transformers which are continuously on duty [1;2; 3]. The reliability considerations require that the rated power S_S of each transformer (here it is called small transformer) is smaller than substation maximum load S_{max} but greater than half of substation maximum load, namely [2]:

$$S_S > 0.71 S_{max} . \quad (1)$$

By this provision it is ensured that, in case of one transformer failure, the remaining on duty transformer takes over the load of faulty transformer and consequently is, in extreme cases of energy supply, loaded to 1.4 of its loading capability. But, as far as such load does not remain for a long time, this load duty is considered to be admissible.

Such adopted approach does not take into account the losses in substation transformers. The thing is that, in most cases, a few transformers have greater summary losses, than a single one. In the concrete, one transformer always has smaller losses than a number of transformers with the same total power [4]. However, if the last condition is not fulfilled, the issue must be considered in each special case, taking into account that reliability concerns demand substation to have more than one transformer. We will halt on substation with two transformers one of which (the big) has rated power S_B above the maximum load:

$$S_B > S_{max} \quad (2)$$

and the second spare transformer (the small) with rated power less than that of the big transformer (see (1)). Two possible modes of this two transformer exploitation are of interest for us: the first mode – on duty is big transformer the small transformer being in reserve all the time; it is alternative option; the second mode – big transformer is on duty during season of the year with greater loads, the small one being on duty in season of smaller loads; it is one at time option. These two modes should be compared with each other and with the adopted option theoretically and in concrete examples.

The transformer losses in contingency cases (with one faulty transformer) are not considered here since contingency condition is not permanent.

In further consideration, the **relative utilization time of power losses** (UTL) τ^* will be used for physical quantity *q(t)* determined on time *t* during any time span (duration) which begins in the beginning moment t_b and continues to the finish moment t_f:

$$\tau_{bf}^{\;*}=\frac{\int_{t_b}^{t_f} q(t)dt}{t_f-t_b} \qquad (3)$$

Then real UTL τ which can be used to compute energy losses during time span $t_f - t_b$ is determined by simple formula

$$\tau_{bf}=\tau_{bf}^{\;*}(t_f-t_b) \qquad (4)$$

II. ADOPTED AND ALTERNATIVE OPTIONS

Such a consideration was made in [5]. Here the main points with some update and numerical data will be presented. In practice, the exact coincidence of maximum load S_{max} and rating of big transformer S_B can hardly be met. Usually maximum load is β times smaller than closest transformer rating; hence we have for alternative option:

$$\beta_B=\frac{S_{\max}}{S_B}, \qquad (5)$$

and for adopted option:

$$\beta_S=\frac{S_{\max}/2}{S_S}\ , \beta_S<1, \qquad (6)$$

where load factors β_B and β_S can vary due to real rated power scale of manufactured transformers.

For big transformer of alternative option with rated power S_B in accordance with (5), power losses ΔP_{al} are:

$$\Delta P_{al}=\Delta P_B=\Delta P_{ldB}(\Delta P_{nlB}^{\;**}+\beta_B^{\;2}\tau_y^{\;*}), \qquad (7)$$

where ΔP_{ldB} and ΔP_{nlB} – load losses and no-load losses of a big transformer; τ_y^* - relative utilization time of power losses (UTL) on span T_y of one year; ΔP_{nlB}^{**} - related no-load losses of big transformer $\Delta P_{nlB}^{\;**}=\Delta P_{nlB}/\Delta P_{ldB}$, β_B – see (5).

Power losses of two transformers of adopted option:

$$\Delta P_{ad}=2\Delta P_{ldS}(\Delta P_{nlS}^{\;**}+\beta_S^{\;2}\tau_y^{\;*}), \qquad (8)$$

where ΔP_{nlS}^{**} is analogical ΔP_{nlB}^{**}; β_S – see (6).

The losses of adopted option ΔP_{ad} can be spelled in other way, taking into account approximate dependences between rated power of transformers and their losses [4]:

$$\Delta P_{ad}=2\sqrt[4]{k_S^{\;3}}\,\Delta P_{ldB}(\Delta P_{nlS}^{\;**}+\beta_S^{\;2}\tau_y^{\;*}), \qquad (9)$$

where k_S – transformer rating ratio $k_S=S_S/S_B$; hence $\beta_S=0,5\beta_B/k_S$, since each small transformer takes half of big transformer load.

Rating ratio of close by transformers roughly is $k_S\approx 0.63$. Related no load losses of manufactured transformer series approximately are equal: $\Delta P_{nlB}^{**}\approx\Delta P_{nlS}^{**}$. With this assumption, we find from (7) and (9), that losses of alternative option will be smaller when substation relative UTL τ^*:

$$\tau^*<\frac{3,8}{\beta_B^{\;2}}\Delta P_{nl}^{\;**}, \qquad (10)$$

which means that alternative option practically always have smaller losses than adopted one. Here we can state an important fact: if rated power ratio remains $k_S\approx 0.63$, the greater rated power of big transformer is (the smaller β_B) the more favorable is alternative option.

As a practical example, using (7) and (8), we have considered four substations: Centrālā, Ogre, Preili and Lielvārde which represent loads of diverse nature and magnitude. The results are shown in table 1. Transformer data are borrowed from [6].

Designations in table 1 are: S_n – transformer rated power; ΔP_l and ΔP_n – transformer load and no load losses; ΔP_{al}, $\Delta P_{ad}'$ and ΔP_{ad} – losses of alternative option, of adopted option with big transformers and with small ones.

We can see that alternative option have less losses with the same reliability of electricity delivery. Besides, alternative option preserve resource of spare transformer since it stands in cold reserve.

TABLE 1
TRANSFORMER LOSSES OF ALTERNATIVE AND ADOPTED OPTIONS

Subst	S_{max}, MVA	τ_y^*	Rated power S_n in MVA; losses ΔP_l, ΔP_n, ΔP_{al}, $\Delta P_{ad}'$, ΔP_{ad} in kW											
			Alternative option					Adopted option						
			S_n	ΔP_l	ΔP_n	β_B	ΔP_{al}	S_n	β_B'	β_S	ΔP_l	ΔP_n	$\Delta P_{ad}'$	ΔP_{ad}
Centr	35.05	0.361	**63**	**310**	**70**	**0.556**	**116**	40	**0.278**	0.438	230	50	**163**	142
Ogre	15.407	0.353	**25**	**145**	**36**	**0.616**	**61.6**	16	**0.308**	0.481	105	26	**84.7**	74.7
Preiļi	7.74	0.404	**10**	**80**	**19**	**0.774**	**44.6**	6,3	**0.387**	0.614	60	14	**50.8**	52
Lielv.	3.072	0.5	**10**	**80**	**19**	**0.372**	**24.2**	6,3	**0.154**	0.244	60	14	**39.8**	31.3
Lielv	3.072	0.355	6,3	60	14	0.488	20.7							

Notes. Bold numbers represent data for actually installed (big) transformers. Ordinary numbers show data of one step lower (small) in transformer nominal' gradation. $\Delta P_{ad}'$ is for the option with two big transformers being permanently in operation; ΔP_{ad} – two small transformers permanently in operation; ΔP_{al} – one big transformer in operation round the year, the second small one being in reserve.

III. ONE AT A TIME OPTION

Considered above alternative option assumes the big transformer to be in operation, the small transformer being in cold reserve all the time. The matter of interest is to clear up whether it is the optimum option when one (the small) transformer whole year remains as spare transformer till some contingency sets it working. We shall consider the third "one at a time" option (OT option) when the big transformer is operating during winter season, the small one – during summer season. This to be done, the following should be ascertained.

Lemma. A UTL relative value in some time span increases if UTL relative value on some duration within the limits of said time span is greater than UTL relative value of remaining duration of said time span.

Proof of the lemma. The UTL τ_{bf} of some quantity $q(t)$ on time span bf (Fig.1) can be expressed as:

$$\tau_{bf} = \int_{t_b}^{t_f} q^2(t)dt = \int_{t_b}^{t_1} q^2(t)dt + \int_{t_1}^{t_2} q^2(t)dt + ... + \int_{t_{n-1}}^{t_f} q^2(t)dt =$$

$$= \frac{(t_1 - t_b)\int_{t_b}^{t_1} q^2(t)dt}{t_1 - t_b} + \frac{(t_2 - t_1)\int_{t_1}^{t_2} q^2(t)dt}{(t_2 - t_1)} + ...$$

$$+ \frac{(t_f - t_{n-1})\int_{t_{n-1}}^{t_f} q^2(t)dt}{t_f - t_{n-1}} = \tau_1^*\Delta t_1 + \tau_2^*\Delta t_2 + ... + \tau_f^*\Delta t_f \qquad (11)$$

where durations Δt are $\Delta t_1 = t_1 - t_b$, $\Delta t_2 = t_2 - t_1$,..., $\Delta t_f = t_f - t_{n-1}$. Relative value of UTL τ_{bf} (see (3)) on duration $t_f - t_b$ is:

$$\tau_{bf}^* = \frac{\tau_{bf}}{t_f - t_b} = \frac{\tau_1^*\Delta t_1}{t_f - t_b} + \frac{\tau_2^*\Delta t_2}{t_f - t_b} + ... + \frac{\tau_f^*\Delta t_f}{t_f - t_b} \qquad (12)$$

Expression (12) shows that UTL relative value on time span *bf* is the time mean weighted of constituent UTL relative values. Hence it follows that, relative value increases with any UTL relative values constituent of this time span. *Lemma is proven*.

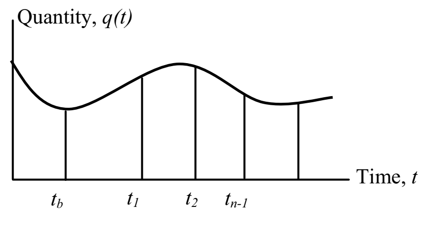

Fig. 1. Decomposition of quantity q(t) graph for UTL calculation

For further consideration, we shall introduce the notion of effective relative UTL τ_e^*:

$$\tau_e^* = \beta_B^2 \tau^*, \qquad (13)$$

where load factor $\beta_B = S/S_B$ – the ratio of load duration curve (LDC) current value to the rated power of big transformer; τ^* - current relative UTL on the part of load duration curve from S to S_{min} (Fig.2).

Theorem. Effective relative UTL increases with load factor.

Proof of the theorem. Let us consider UTL of trapezium I (Fig.2). Trapezium relative UTL $\tau_{t,I}^*$ on duration Δt_1 according to [7] is:

$$\tau_{t,I}^* = S_{min}^* + (1/3)(1 - S_{min}^*)^2 = = (1/3)(1 + S_{min}^* + S_{min}^{*2}) \qquad (14)$$

Observing that $S_{min}^* = S_{min}/S_1$ and $S_{min} = \beta_0 S_B$; $S_1 = \beta_1 S_B$; ...; $S_n = \beta_n S_B$, where S_B –some quantity $S_B > S_n$, we have relative UTL for trapezium I, trapezium II (on duration Δt_2) and for two trapezia I+II on (duration $\Delta t_1 + \Delta t_2$):

$$\tau_{t,I}^* = \frac{1}{3}[1 + \frac{\beta_0}{\beta_1} + (\frac{\beta_0}{\beta_1})^2];$$

$$\tau_{t,II}^* = \frac{1}{3}[1 + \frac{\beta_1}{\beta_2} + (\frac{\beta_1}{\beta_2})^2];$$

$$\tau_{t,I+II}^* = \frac{\frac{1}{3}[1 + \frac{\beta_1}{\beta_2} + (\frac{\beta_1}{\beta_2})^2]\Delta t_2 + \frac{1}{3}(\frac{\beta_1}{\beta_2})^2 \tau_{t,I}^* \Delta t_1}{\Delta t_2 + \Delta t_1} \qquad (15)$$

Now we consider effective relative UTL. For first trapezium we have:

$$\tau_{te,I}^* = \beta_1^2 \tau_{t,I}^* = (1/3)[\beta_1^2 + \beta_1\beta_0 + \beta_0^2] \qquad (16)$$

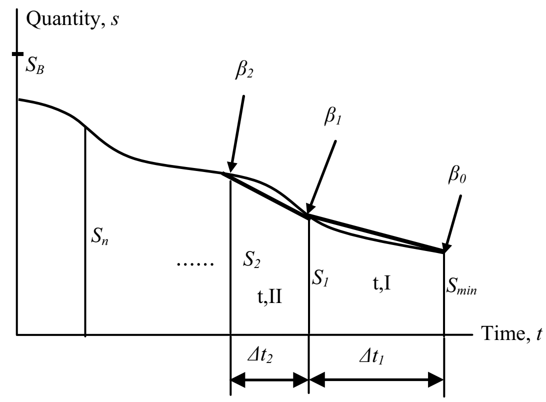

Fig.2. Decomposition of load duration curve on trapezia t,I, t,II and so on

For the sum of trapezia t,I and t,II we have:

$$\tau_{te,I+II}{}^{*} = \frac{(1/3)(\beta_2{}^2 + \beta_2\beta_1 + \beta_1{}^2)\Delta t_2}{\Delta t_2 + \Delta t_1} + \frac{(1/3)(\beta_1{}^2 + \beta_1\beta_0 + \beta_0{}^2)\Delta t_1}{\Delta t_2 + \Delta t_1} \quad (17)$$

By force of lemma and since $\beta_0<\beta_1<\beta_2$:

$$\tau_{te,I+II}{}^{*} > \tau_{te,I}{}^{*} \quad (18)$$

When we consider the third trapezium, the first one can be changed by the second and out of the same reasons we shall have $\tau_{te,I+II+III}{}^{*}>\tau_{te,II+II}{}^{*}>\tau_{te,I+II}{}^{*}$ and so on, provided β is growing. *Theorem is proven*.

By force of the theorem, entire LDC can be decomposed on trapezia and its effective relative UTL will increase or decrease with load factor β increasing or decreasing. The durations Δt can be taken so small that the theorem is true for smooth LDC.

Big transformer must be in operation in the season of year comprising winter (winter season) at least due to overloading constraint of small transformer. But at some place of substation LDC (between $t^*=0$ and 1) which corresponds to season comprising summer (the summer season) it is worthwhile to see whether losses of small transformer ΔP_{sseS} are less than those ΔP_{sseB} of big one. The turning-point is marked by expression:

$$\Delta P_{sseS} \le \Delta P_{sseB} \quad (19)$$

The losses of big transformer in summer season beginning with load factor β_{sseB}:

$$\Delta P_{sseB} = \Delta P_{ldB}(\Delta P_{nlB}{}^{**} + \beta_{sseB}{}^2 \tau_{sse}{}^{*}). \quad (20)$$

where $\tau_{sse}{}^{*}$ - UTL in summer season. For small transformer, the losses will be

$$\Delta P_{sseS} = \Delta P_{ldS}(\Delta P_{nlS}{}^{**} + \beta_{sseS}{}^2 \tau_{sse}{}^{*}) = \\ = \Delta P_{ldS}(\Delta P_{nlS}{}^{**} + \frac{\beta_{sseB}{}^2}{k_S{}^2}\tau_{sse}{}^{*}) \quad (21)$$

From last two expressions we find that (19) is in force when

$$\Delta P_{nlB} - \Delta P_{nlS} \ge \tau_{sseeB}{}^{*}(\frac{\Delta P_{ldS}}{k_S{}^2} - \Delta P_{ldB}), \quad (22)$$

where $\tau_{sseeB}{}^{*}$ - effective UTL of summer season.

The small transformer will have smaller losses than big one when effective relative UTL $\tau_{sseeB}{}^{*}$ during summer season will be smaller than threshold value $\tau_{ethr}{}^{*}$ determined by expression (23):

$$\tau_{sseeB}{}^{*} < \tau_{ethr}{}^{*} = \frac{\Delta P_{nlB} - \Delta P_{nlS}}{\frac{\Delta P_{ldS}}{k_S{}^2} - \Delta P_{ldB}} \quad (23)$$

When we assume: 1) k_S=0,63; 2) $\Delta P_{nlS} = \sqrt[4]{k_S{}^3}\Delta P_{nlB}$; 3) $\Delta P_{ldS} = \sqrt[4]{k_S{}^3}\Delta P_{ldB}$; $\Delta P_{nlB}{}^{**}=\Delta P_{nlS}{}^{**}=0.2$,

than $\tau_{ethr}{}^{*} = 0.075$.

The threshold value of effective relative UTL $\tau_{ethr}{}^{*}$ sets in when load factor β_B decreases to its threshold value β_{Bthr} which is when the load is S_{thr}. According to the theorem, further β_B diminishing will diminish effective relative UTL $\tau_{sseeB}{}^{*}$ and stipulation (19) will be fulfilled.

In order to minimize energy losses in substation transformers, transition from winter season to summer season by changing the big transformer for small transformer must be undertaken at once when effective relative UTL $\tau_{sseeB}{}^{*}$ reaches the value $\tau_{ethr}{}^{*}$.

Now the question is: how to determine the necessary dates of the year for transformer change over? The answer is: within these dates of the year the effective relative UTL $\tau_{sseeB}{}^{*}$ should satisfy (23).

Take some day on the boundary of winter and summer seasons. Determine β_B by (5) for maximum load of this day. Take some day on the boundary of summer and winter seasons with approximately the same β_B. Determine relative UTL $\tau_{sse}{}^{*}$ in duration between this two dates and then effective value $\tau_{ssee}{}^{*}$ by (13). If this $\tau_{ssee}{}^{*}$ satisfies (23) than change over dates are determined, otherwise try some other dates.

In this procedure the question how to determine relative value of UTL $\tau_{sse}{}^{*}$ for summer season is fallen out. This quantity can be found by any known method using load graphs of previous year. If consumed energy MVA in sought for summer season is known out of energy counter data, then the necessary summer season relative UTL can be found by approximate Kazewich formula

$$\tau^* = (0.124 + \frac{T_m^*}{1.142})^2 \quad (24)$$

or by more exact formula [7]:

$$\tau^* = S_{\min}^*[S_{\min}^* + 2(T_m^* - S_{\min}^*)] + \\ + [(p + q\frac{T_m^* - S_{\min}^*}{1 - S_{\min}^*})(1 - S_{\min}^*)]^2 \quad (25)$$

Coefficients for LDC in the shape of straight line (trapezium) are p=0.135; q=0.885; they may slightly change for convex, concave shape and for "S" or inverse "S" shape of the LDC. The procedure is following. The graph of **daily maximum** loads in MVA is build for period greater than summer season (Fig.3). Horizontal line a at height of assumed S_a=S_{max} (this is daily maximum) of summer season shows the spring and autumn dates d_{spr} and d_{aut} for assumed period of summer season. The consumed energy A, MVA of this assumed season may be known out of electricity counter readings. The daily minimum load S_{mm} in the graph of day of minimum daily consumption is determined. In this day maximum load S_M is the smallest of all maximum loads of the season. Now the necessary quantities for formulas (24); (25) can be determined:

$$T_m = \frac{A}{S_{\max}};\ T_m^* = \frac{T_m}{t_{daut} - t_{dspr}};\ S_{\min}^* = \frac{S_{\min}}{S_{\max}} \quad (26)$$

Relative UTL τ_{sse}^* are calculated by (24) or (25), β_B by (5) and τ_{ssee}^* by (13). If this τ_{ssee}^* is sufficiently close to the value of τ_{ethr}^* by (23), the dates of transformer switch over can be considered determined, otherwise new position of line a should be chosen and calculations made anew.

Yearly energy losses ΔA for substations and options according to table 1 and for OT option are shown in table 2.

As can be seen, the savings in alternative and OT options are not so remarkable. However it can be clearly seen that neither the two big transformers nor two small ones permanently in operation are reasonable solution as in sense of capital investments (two big transformers) and of operation expenses (energy losses).

TABLE 2
SUBSTATION YEARLY LOSSES ΔA in POWER TRANSFORMERS (KWh)

Substation	ΔA_{ad}'	ΔA_{ad}	ΔA_{al}	ΔA_{OT}
Centrāla	1427880	1243920	1016160	924960
Ogre	741972	654372	539616	496960
Preiļi	445008	455520	390696	371496
Lielvārde	348648	274188	211992	183192
Lielvārde			181332	

Note. ΔA_{ad}', ΔA_{ad}, ΔA_{al} – data according to options in table 1; ΔA_{OT} – big transformer (now installed) busy in winter season, the small one – in summer season.

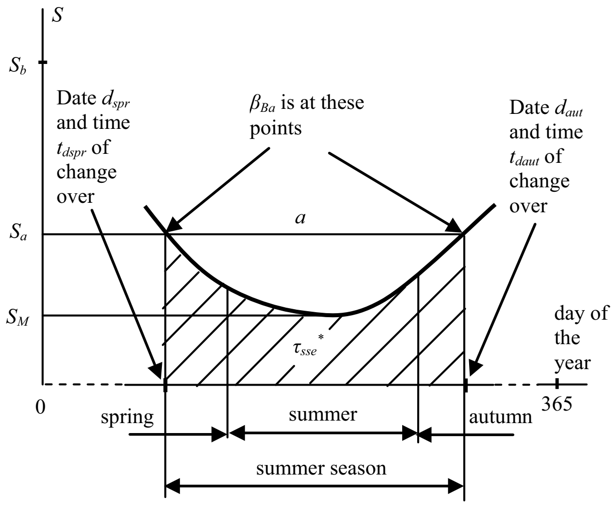

Fig. 3. Determination of transformer change over dates

However reliability constraints demand two transformers in a substation. The inference is: one transformer busy, the second one idle.

This option is now practiced in Latvia: one transformer on duty, the second – in reserve. The thing which is now to be resolved upon: is it more practicable to have in a substation two equal transformers or to install the big transformer and the small one which are shifted for one another once a year. So far can be recognized that the last option demands smaller capital investments (the small transformer is cheaper than big one) and less expenditures (losses ΔA_{OT} are the least).

Still one option may be considered which may be considered as improved adopted option, namely: two small transformers are in operation during cold season, in warm season one small transformer remains in operation. In sense of energy losses this option yields to OT option since during cold season its energy losses are greater than those of alternate option notwithstanding some increase of UTL during cold season. The reader can verify himself in numbers this assertion.

IV. ASSESSMENT OF THE BENEFIT AND SHORTCOMING FROM INTRODUCTION OF ONE AT A TIME OPTION INSTEAD OF ADOPTED OPTION

The assessment of the benefit is made approximately based on publicly available data of Latvenergo power system. The figures of table 2 are used as initial inputs. First, the sum of transformer yearly losses of substation Centrālā, Ogre, Preiļi and Lielvārde of adopted option $\Sigma\Delta A_{ad}$ and of OT option $\Sigma\Delta A_{OT}$ is calculated: $\Sigma\Delta A_{ad}$ = 2628000 kWh; $\Sigma\Delta A_{OT}$ = 1976608 kWh. The relative difference D_r of these amounts is determined:

$$D_r = \frac{\Sigma\Delta A_{ad} - \Sigma\Delta A_{OT}}{\Sigma\Delta A_{ad}} \quad (27)$$

and it equals D_r=0.25. The sum of actually installed transformer capacity ΣS_n of said four substations is determined based on table 1: ΣS_n = 63 x 2 + 25 x 2 + 10 x 2 + 10 x 2 = 216 MVA. From [8] we find that in 2007 installed power of all 110 kV transformers is S_{n110} = 4402.8 MVA and of all 330 kV transformers S_{n330} = 3075 MVA. Since total installed capacity of high and extra high voltage transformers S_{ntot} = 7478 MVA. Overwhelming majority of substations contain two transformers. Hence we can estimate total amount of transformer losses ΔA_{adtot} as being proportional to total installed transformer capacity S_{ntot}:

$$\Delta A_{adtot} = \Sigma\Delta A_{ad} \frac{S_{ntot}}{\Sigma S_n} \quad (28)$$

and it equals ΔA_{adtot}= 91 GWh. The electricity savings can be defined as:

$$\Delta A_{ben} = D_r \Delta A_{adtot} \quad (29)$$

which equals ΔA_{ben}=22.7 GWh, that in relation to the 2007 annual consumption of electricity [9] is 0.34 %.

The second side of this issue should be considered – the resource wear of the substation transformers. Clarification of this side of the issue can be done, based on rough calculations. According to Arenius's law [10], 6 °C excess of temperature reduces lifetime of transformer by half. The big transformer of OT option is selected so that it bears its rated load S_{max}, than its power losses are:

$$\Delta P_{OT} = \Delta P_{ld} (\Delta P_{nl}^{**} + \tau^{*}) \quad (30)$$

Transformer in adopted option is loaded to 0.71S_{max}, hence its power losses are:

$$\Delta P_{ad} = \Delta P_{ld} (\Delta P_{nl}^{**} + \beta^2 \tau^{*}) = \Delta P_{ld} (\Delta P_{nl}^{**} + 0{,}5\tau^{*}) \quad (31)$$

Admissible temperature inside the transformer tank at rated loading of the transformer is assumed to be 98 ° C. With mean outdoor annual temperature 15 °C, temperature difference which transfers the OT transformer losses ΔP_{OT} to external environment is ΔT_{OT} =83 °C. In turn, temperature difference which transfers losses of the adopted option is:

$$\Delta T_{ad} = \Delta T_{OT} \frac{\Delta P_{ad}}{\Delta P_{OT}} = \frac{\Delta P_{nl}^{**} + 0.5\tau^{*}}{\Delta P_{nl}^{**} + \tau^{*}} \quad (32)$$

By assumed relative UTL τ^*=0.5 and average related no-load losses ΔP_{nl}^{**}=0.25, temperature difference of adopted option is ΔT_{ad}=55.3 °C. It means that insulation of transformers of adopted option is heated by 42.7 °C less than in case of OT option. As a result, lifetime of transformers of OT option is much less than in case of adopted option despite the fact that transformers of OT option are in operation only for approximately half the time. To get rid of this shortcoming, transformers of OT option should be cooled more intensively or their design must provide more intensive cooling.

V. CONCLUSIONS

1. Out of reliability considerations of electricity supply, two transformer option of substation is necessary.
2. From viewpoint of electricity losses, simultaneous operation of several substation transformers is disadvantageous as compared with one transformer of the summary rated power; hence two transformers permanently in operation has no advantage against single transformer.
3. Out of considerations of substation losses, substation transformers should not be of equal rated power, the small transformer being on duty in summer season, the big one – in winter season.
4. The big transformer must have power rating to cover maximum substation load being loaded to allowable limits, power of the small transformer to be one step below.
5. Approximate calculations show that the use of OT option with different power transformers would save about 23 GWh energy per year in Latvenergo company representing 0.34 % of consumed electrical energy in year 2007.
6. Rough estimation shows that, in order to retain transformer lifetime of OT option substation on the level of adopted option substation, it is necessary to intensify the cooling of transformers.

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