# Once again on loading and capacity selection of autotransformers in transmission grids

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**Abstract.** The aspects which have a bearing upon selection of capacity of autotransformers, such as load graphs, permissible temperature characteristics, n-1, n-2 modes, are considered. On the basis of statistical analysis suggestions for improving the current method of capacity selection of autotransformers in transmission grids are given.

## 1 Introduction

In previous work [1], authors considered aspects of choosing the power of autotransformers (AT) installed on 220-750 kV substations. It was noted that the capacity of these autotransformers is selected under uncertainty, since we need to predict the operation conditions for the period of 10 years and more (referring to scheme of power system development).

The following problems have been identified:

The scope of regulation of current standard [2] does not include loading capacity of most of the transformer equipment installed in transmission grids, namely 220-750 kV autotransformers with 125-800 MVA capacity and OF cooling system. Thus, its lack of the methodical base for taking a correct decision.

Lastly, it has become customary to consider every possible condition (mode) in the power system for capacity selection of autotransformers during design of substations. Not only do we include n-1modes (with failure of one grid element), but also n-2 modes (with failure of two concurrent grid elements). And mode with autotransformer loading higher than in n-1 mode can always be found.

On top of that, the tendency for industrial load decreasing from the 1990s, the limited number of unit sizes, and cautious attitude of the operating organizations to transformer overloading are added [5].

Under these circumstances a low load of costly transformer equipment appears.

In this paper, the authors set a goal to update the previous study, taking into account a wider sample of data, to confirm or refute the previously obtained results, and propose a scientifically substantiated recommendation for the capacity selection of 220 - 750 kV autotransformers in transmission grids.

## 2 Accounting for load graphs

The real daily measurement data of check measurement days in 2015, 2020, and 2021 years for more than 300 substations according with their voltage type were analyzed and the values of characteristic equivalent two-stage load graphs of 220-500 kV substations from different regions of the country were obtained. Results are given in the Table 1.

Defined:

– load factor $f_{\text{load}}$ (the average load divided by the peak load);

– load curve irregularity factor $f_{\text{irreg}}$ (the minimum load divided by the peak load).

– $f_{\max}$ factor, calculated as the winter peak load ($S_{\max(w)}$) divided by the summer peak load ($S_{\max(s)}$);

The mean value of $f_{\max}$ is still equal to 1.2. Likewise, for about 30% substations the summer peak load is higher than the winter peak load. Geographically these substations are located in all regions of the country (not only in southern regions). It is harder design condition, since rated autotransformer capacity conform to ambient temperature of 20°C, i.e. permissible loading is decreasing while growth of temperature and conversely.

Mean values of load factor and load curve irregularity factor are $f_{\text{load}}=0.829$ and $f_{\text{irreg}}=0.644$. Therefore, mean pre-load - $K_1$ of equivalent two-stage load graph is in relatively thin range from 0.644 to 0.829 (further arithmetical averages were taken).

Daily load graph characteristics in the Table 1 organized by four groups: 1 group – industrial load, presented in oil production regions of the country enhanced by high share of hydro power plants in the generation mix in some cases; 2 group – regions with large industrial centers and cities; 3– regions with mixed type of load with measurable share of domestic consumer

*Corresponding author: vasilenkone.ird@gmail.com and service sector demand; And the 4th group – the same as the third group, but with high share of agricultural industry.

As shown by the Table 1 the $K_1$ values of equivalent load graphs could be different. These values are varying from 0.69 to 0.81 with almost constant duration of overload h≈8–9 hours. The deviation of the $f_{\text{load}}$, $f_{\text{irreg}}$ for 2015, 2020 and 2021 years is about 1.5%, so the prevalent type of load in the regions under consideration has not changed over the years.

Thermal model of ageing of transformer insulation, top-oil and hot-spot temperature limitations and number of other boundary conditions [2,3] are the foundation of Russian and international methods of definition of loading capacity of autotransformers. In assessment of insulation ageing the known 6°C principle is used. However, permitted temperatures in Russian and international standards [2,3] are different. The comparison is shown in Table 2. The international standards are more sparing. The new standard IEC 60076 – 7 – 2018. “Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers” was published in 2018, which, however, in terms of permissible loading characteristics complies with the previous standard IEC 60076 – 7:2005. Thus, maximum permissible winding hot-spot temperature from [2] - 160°C, while in [3] – 140°C (Table 2).

Examples of loading of autotransformers are given in Fig. 1: solid lines – normal cyclic loading, dashed lines - emergency loading. Curves in Fig. 1 are given for equivalent ambient temperature of +20°C, curves in Fig. 1(a) are given for –10°C and for +20°C in Fig. 1(b). It is common for Moscow region for winter and summer periods thoroughly. Calculations were settled by the procedure [3]. Normal cyclic loadings were calculated with daily loss of life is less than 1. Numbers with daggers in Fig. 1 - duration (h) of overloading $K_2$. The current limitation from Table 2, which is $K_2 \leq 1.3$, is disregarded in Fig. 1

Thus, the conclusions obtained earlier in [1] continue to be relevant.

**Table 1** Characteristics of Equivalent two-stage load graph

| Prevalent type of load | $f_{\text{loa}}$, pu. | $f_{\text{irreg}}$, pu. | $K_1$, pu. | $K_2$, pu. | $h$, h |
|---|---|---|---|---|---|
| 1 group – industrial load (regions of Siberia) | 0.874 | 0.747 | 0.811 | 1 | 8.1 |
| 2 group – regions with large industrial centers and cities (regions of Ural) | 0.823 | 0.643 | 0.733 | 1 | 8.1 |
| 3 group – mixed load (Central regions) | 0.810 | 0.605 | 0.708 | 1 | 8.4 |
| 4 group – mixed load with high share of agricultural industry (South regions) | 0.807 | 0.583 | 0.695 | 1 | 8.8 |
| Mean value | 0.829 | 0.644 | 0.736 | 1 | 8.3 |

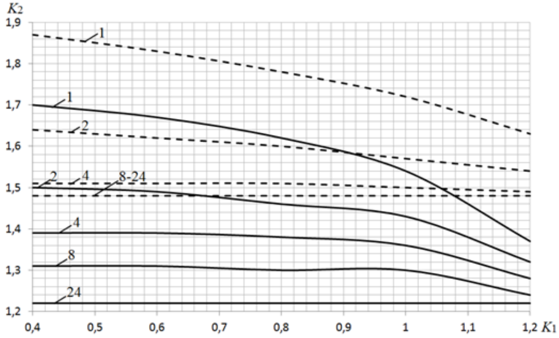

**Fig. 1.a** Loading of AT which rating over 100 MV·A with OF cooling system for –10 °C.

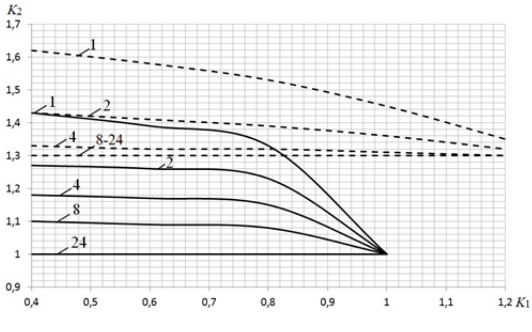

**Fig. 1.b** Loading of AT which rating over 100 MV·A with OF cooling system for +20°C.

Namely:

- loading of autotransformers for the real values $K_1$ from 0.6 to 0.8 and $h$≈8–9 h in transmission grid in Russia (presented in Table 1) are almost constant

- Normal cyclic loads can be limited not by daily loss of life, but the maximum permissible winding hot-spot temperature (120 °C – Table 2).

Permissible cyclic loading of autotransformers with 125-800 MVA capacity and OF cooling system is given in Table 3 for equivalent ambient temperature +20 °C (numerator) and corresponding daily loss of life (denominator).

The comparison of data from Table 1 and Fig. 1,b shows: with removing constraints from daily loss of life under other factors being equal the permissible loading $K_2$ is growing from 1.0 to 1.16. In this case daily loss of life for duration of 8 hours doesn’t exceeded 3.98. Thus, in calendar day insulation is really “aged” on 3.98 days. If annual mean outage doesn't exceed, assume, a month then insulation will be aged on 120 days for this period.

In a steady state mode when two AT are in service and the loading of each is $(1.16/2)S_{\text{rated}}$, the daily loss of life is less than 0,01 (the winding hot-spot temperature is 57 °C), so it can be neglected. This state is common to temperatures up to 80 °C [4]. Thus, determination of permissible cyclic loading based on winding hot-spot temperature is proven design condition for increasing of AT loading. Moreover, the newly introduced transformer equipment is equipped with digital control devices that allow calculating the actual insulation depreciation along the process.

Less stringent requirements are imposed by the industry instruction [6] for the loading of AT with a capacity of more than 100 MV·A with an OF cooling system (Table 4).

**Table 2** Maximum permissible characteristics of autotransformers

| Characteristic | autotransformers capacity, MV·A | | |
|---|---|---|---|
| | below 2.5 | from 2.5 to 100 | above 100 |
| *Normal cyclic load:* | | | |
| Current, pu. | 1.5/1.5/1.5 | 1.5/1.5/1.5 | **/1.3/1.3 |
| Winding hot-spot temperature, °C | 140/140/120 | 140/140/120 | **/120/120 |
| Top-oil temperature, °C | 95/105/105 | 95/105/105 | **/105/105 |
| *Long-time emergency loading:* | | | |
| Current, pu. | 2.0/1.8/1.8 | 2.0/1.5/1.5 | **/1.3/1.3 |
| Winding hot-spot temperature, °C | 160/150/140 | 160*(140*)/140/140 | **/130/140 |
| Top-oil temperature, °C | 115/115/115 | 115/115/115 | **/115/115 |

Note: the first number – from GOST 14209 – 85; the second – from IEC 60354 – 91, the third – from IEC 60076 – 7:2018; * the first number for transformers up to 110 kV, the second – above 110 kV ** – not rated

**Table 3** Cyclic loading and daily insulation loss of life for winding hot-spot temperature of 120°C

| Overload duration, h | Permissible overload $K_2$ for $K_1$ | | | |
|---|---|---|---|---|
| | $K_1 = 0.4$ | $K_1 = 0.6$ | $K_1 = 0.8$ | $K_1 = 1.0$ |
| 1.0 | $\frac{1,43}{0,60}$ | $\frac{1,39}{0,64}$ | $\frac{1,33}{0,77}$ | $\frac{1,25}{1,89}$ |
| 2.0 | $\frac{1,27}{0,61}$ | $\frac{1,26}{0,67}$ | $\frac{1,23}{0,78}$ | $\frac{1,20}{1,90}$ |
| 4.0 | $\frac{1,19}{1,05}$ | $\frac{1,18}{1,06}$ | $\frac{1,18}{1,35}$ | $\frac{1,17}{2,47}$ |
| 8.0 | $\frac{1,16}{2,44}$ | $\frac{1,16}{2,57}$ | $\frac{1,16}{2,85}$ | $\frac{1,16}{3,98}$ |
| 24.0 | $\frac{1,16}{11,10}$ | $\frac{1,16}{11,20}$ | $\frac{1,16}{11,46}$ | $\frac{1,16}{11,77}$ |

Permissible emergency overload $K_2$ = 1.1-1.5 in Table 4, while from the positions of the permissible current load according to [3] from Table 2 $K_2 \leq 1.3$ (more stringent design condition). These differences, apparently, should be taken into account by operating organizations and manufacturing plants of transformer equipment.

**Table 4** Permissible emergency overload of autotransformers

| Overload duration, h | Permissible overload $K_2$ at ambient temperature, °C | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | –25 | –20 | –10 | 0 | +10 | +20 | +30 | +40 |
| 1.0 | 1.6 | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.2 | 1.2 |
| 2.0 | 1.5 | 1.5 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.1 |
| 4.0 | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.2 | 1.2 | 1.1 |
| 8.0 | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.2 | 1.2 | 1.1 |
| 24.0 | 1.5 | 1.5 | 1.4 | 1.4 | 1.3 | 1.2 | 1.2 | 1.1 |

## 3 Accounting for n-1 modes

As it is known, the nominal parameters of electrical devices are selected according to the normal mode and checked for maintenance and postfault mode. In this regard, 153 two-transformer substations were selected: 220/110 (103 substations) and 500/110-220 kV (50 substations). For them, the power flow calculations in the grid were carried out in the n–1 mode (when one of the autotransformers was turned off). The electric grid model was also formed based on actual measurements on regime days 2014–2016 yrs. Accumulation curves of the load distribution of autotransformers in normal mode in relation to their rated capacity in 2020 is determined as the arithmetic mean value of the power of autotransformers per day (winter or summer regime day) in relation to the rated capacity according to 124 substations (107 - 220 kV substations, 24 - 330 kV substations, 49 - 500 kV substations)

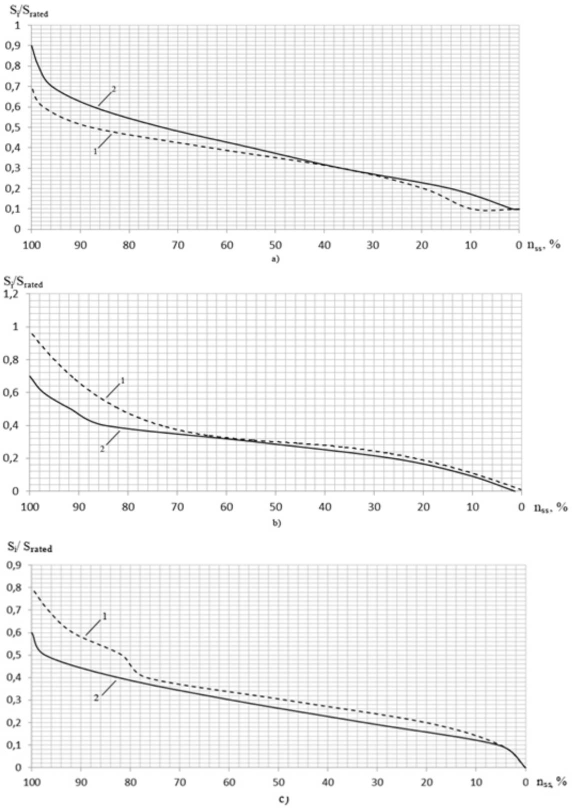

**Fig. 2** Integral load distribution of AT $S_{normal}/S_{rated}$ according to data from 2015 (a),2020 (b), and 2021(c) years: 1 – for 220 kV substations, 2 – for 500 kV (a) and 330-500 kV (b,c)

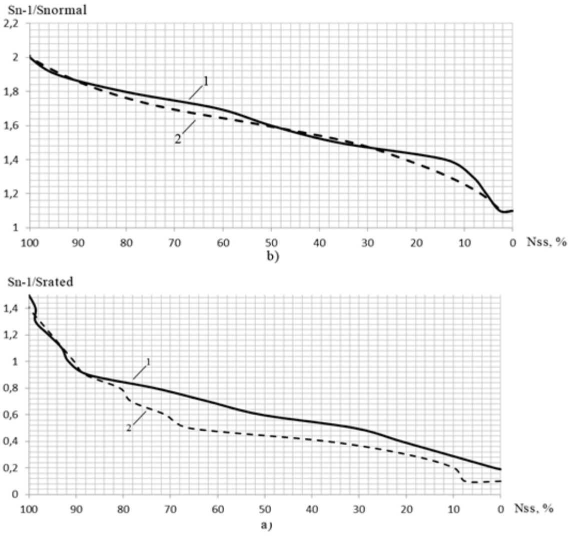

**Fig. 3** Integral load distribution of AT $S_{n-1}/S_{rated}$ (a) and $S_{n-1}/S_{normal}$ (b): 1 – for 220 kV substations, 2 – for 500 kV

The distribution of loads of autotransformers in normal mode ($S_{normal}$) and in n – 1 mode ($S_{n-1}$), referred to their rated power ($S_{rated}$) and normal load ($S_{normal}$) are shown in Fig. 2-3. The predominant loads of autotransformers in normal mode are concentrated in the area $S_{normal}/S_{rated} << 0.6$. In the n–1 mode, the load rises to $S_{n-1}/ S_{rated} << 1.5$. In this regard, the $S_{n-1}/ S_{rated}$ distribution curve is more indicative. Here the load of autotransformers increases by 1.1-2.0 times compared to that for normal operation; the average value of $S_{n-1}/S_{rated} = 1.5$, and the maximum value is 2.0. The last value is typical for single-ended substation, when the entire load falls on the autotransformer remaining in operation. The average value of 1.5 in the n–1 mode characterizes the generalized effect of grids of adjacent voltage levels on the resulting power flow in the electrical grid.

In other words, when one of the autotransformers is out-of-operation, its load is approximately equally distributed over the grid between the shunt connections of other voltage levels and the autotransformer that remains in operation. Thus, the connection scheme (configuration) of electrical grids is a significant influencing factor in the justification and selection of the power of autotransformers in the transmission grids of power systems.

In 90% of autotransformers, the relative load in the n–1 mode does not exceed 1.0, i.e. rated capacity of the corresponding autotransformers. In this regard, it can be assumed that their rated capacity is selected in the transmission grids of the country's power systems is not entirely rational, since it practically does not take into account the available overload capacity of transformer equipment.

To confirm this conclusion, a correlation analysis was carried out between the years of commissioning of autotransformers (Fig. 4) and their loading in the n–1 mode (during the analysis, 108 substations 220 and 500 kV were selected).

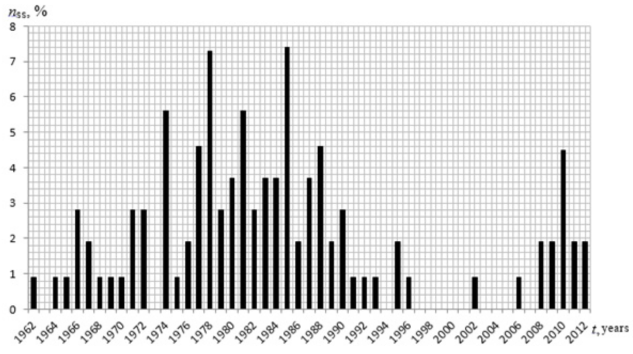

**Fig. 4** Distribution of commissioning of the considered autotransformers by years.

Calculations have shown that the correlation coefficient between the load of autotransformers and their year of commissioning is 0.09, which indicates the absence of cause-and-effect relationships here.

## 4 Accounting for n-2 modes

In [1] there were calculated AT loadings $S_{n\text{-}1}$ and $S_{n\text{-}2}$ on 73 two-transformer substations with voltage level from 220 kV to 500 kV in $n$–1 and $n$–2 modes in all regions of the country for peak loading scheme of 2015 year. N-1 modes were modeled with failure of one autotransformer. In n-2 modes all OHL 110 kV and above in a corresponding region were orderly and sequential failured in addition to failure of one autotransformer (more specifically – with one autotransformer out-of-operation due to scheduled maintenance) n-1 modes. For one particular substation, the number of modes was in the range of 100 to 400.

Obtained results:

– from 16073 $n$–2 modes - 4919 modes (about 30%) lead to excess $S_{n\text{-}2}>S_{n\text{-}1}$;

– from these 4919 modes - 4718 design conditions (95.9%) lead to excess of autotransformer loading less than 0.1 in comparison with the same in $n$–1 mode and 4718+115=4833 (98.3%) – less than 0.2;

– the number of modes, where $S_{n\text{-}2}/S_{n\text{-}1}>1.1$, decreases rapidly with increasing of power surge;

– between 16073 design modes there was found one extreme event with $S_{n\text{-}2}/S_{n\text{-}1}=1.81$.

It should be noted that the ratio $\mathrm{S}_{n\text{-}2}/\mathrm{S}_{n\text{-}1} >> 1.0$ only in 20% of cases was caused by the failure of the overhead line from the substation under consideration. Another 30% were added by failure of overhead lines, which evacuated the power of power plants. The remaining 50% are other failures.

As was shown, ceteris paribus, permissible emergency overloads are 0.2–0.3 higher than systematic loads. Thus, if capacity of autotransformers is selected according to n-1 mode, then while verify it in n-2 mode we can exclude 98.3% design conditions from consideration, $S_{n\text{-}2}/S_{n\text{-}1}<1.2$. Next, in [1] reliability evaluation of n-1 modem, but authors could not found even one for reliability evaluation. In a point of fact, in the majority of cases rated capacity of autotransformers installed are exceed power flows through autotransformers not only in n-1 mode, but also in n-2 mode. In other words, rated capacities of given autotransformers due to various reasons turn out to be such uprated, that it's impossible to estimate real limitations for doing reliability evaluation.

Further, in [1], the reliability evaluation of n–2 modes was conducted using the example of a real 220/110 kV substation with $S_{\text{rated}}$=250 MV·A.. According to the results of the calculation of modes, it turned out that in the most severe n-2 mode, there is a limitation on power transmission in the amount of 37 MW. Further, the calculation of the resulting value of the undersupply of electricity was made, taking into account the reliability parameters of the grid elements for the 3 most severe n-2 modes.

It is shown that in order to eliminate restrictions on power flows in n–2 modes in the scheme of the substation under consideration, one can go for the option of increasing the autotransformers' capacity from 125 to 200 MV·A. With the maximum recommended value of specific damage of 240 rub./(kW·h) economic consequences due to the unreliability of the scheme for $\Delta W \approx 4.0$ MWh will amount to 10.8 million rubles. while the costs associated with an increase in the rated power of the AT, 134 million rubles, i.e. about an order of magnitude higher

## Conclusion

1. It was revealed that since 2015 the average load of autotransformers installed in transmission grids of the country has retained its value, as well as the characteristic load curves by region, foreign approaches to determining the load capacity of AT have not fundamentally changed.

2. The parameters of the actual equivalent load graphs of substations in transmission grids may differ significantly across the regions of the country. The revealed preload is within a wide range of 0.6 - 0.9 with an overload duration of 8-9 h. However, the permissible loading of autotransformers in this case turns out to be practically unchanged, which is fundamentally important when assessing it for a given perspective.

3. The existing cumbersome practice of justifying and choosing the capacity of autotransformers in transmission grids, taking into account not only the n–1 modes, but also hundreds and thousands of n-2 modes, is redundant. It is not possible to substantiate the advisability of increasing the capacity of autotransformers in n–2 modes even under the most severe design conditions and initial data.

4. The power of autotransformers should be selected based on the maximum power flow in the n–1 mode, i.e. when one of them is disconnected at the substation, taking into account the permissible cyclic loading. -2 modes should be considered only to determine the requirements for emergency automatics.

5. There is an urgent need to revise GOST 14209-85 and expand its provisions to power autotransformers of all standard sizes and increased voltages. One of the options is harmonization with the International Electrotechnical Commission standard, which offers very gentle design conditions for justifying the loading of autotransformers.

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