APPLICATION OF DYNAMIC TRANSFORMER RATINGS TO INCREASE THE RESERVE OF PRIMARY SUBSTATIONS FOR NEW LOAD INTERCONNECTION

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ABSTRACT

This paper presents new approach to determine power reserve of congested primary substations by taking into account the thermal modelling of power transformers. As novelty, the proposed approach considers the uncertainty of thermal model's input parameters - annual ambient temperature variation and annual irregularity of new consumer's load profile. The approach suggested ensures power transformers to continue operation within the acceptable thermal parameters when new consumers are interconnected for this reserve value. The proposed approach is evaluated for real primary substation, located at Tomsk, Russia. The results are compared with conventional approach for reserve determination.

INTRODUCTION

Distribution system operators (DSO) are responsible for interconnection of new consumers. To achieve this mission, DSO calculates the available power reserve/headroom (in MW) of power transformers at primary substation. Traditionally for primary substation with two transformers, reserve is calculated as the difference between transformer nominal rating in N-1 mode and peak load with consideration of forecasted demand growth.

This approach seems to be simple and robust but it does not consider factors such as ambient temperature and power flows over the year, which do affect the admissible power transformer loading. The admissible loading of power transformer with respect to above-mentioned factors could be defined by dynamic transformer ratings (DTR) [1, 2]. To have practical application of DTR for reserve determination, it is necessary to consider probabilistic variations of load and ambient temperature over year. Otherwise, wrong estimation of these factors could lead to unacceptable loading of power transformer, which finally results in power transformer failure.

Thus, the goal of this paper is to improve the current method for substation reserve estimation to consider the load and ambient temperature variation over the year as well as their uncertainties.

DTR could be defined by the thermal modelling of power transformer for given load and ambient temperature conditions. Transformer thermal model usually estimates the hot spot temperature (HST) of windings and associated loss of insulation life (LoL) [3]. These parameters are then used as thermal limits for reserve determination at primary substation.

PROBLEM FORMULATION

As the objective function, we maximize substation reserve, which could be additionally interconnected to congested primary substation by considering the transformer thermal modelling in N-1 mode as well as input data uncertainty:

$$\text{Substation reserve} \rightarrow \max$$

As constraints, we use the highest HST of transformer windings and corresponding LoL:

$$HST_{max} \leq 120\ °\text{C}$$
$$LoL \leq 8\,760\ hours$$

The HST constraint - 120˚C is HST limit for normal cyclic loading defined in IEC 60076-7:2005. This HST limit could be also justified for old transformers, which could have moisture content about 3.5-4% in oil-insulation system by the end of their service life. This moisture content decreases the HST of gas bubble formation from 140℃ (for normal moisture content 1%) to 120℃ [4]. The gas bubbles formation in oil-insulation system could lead to partial discharge inside of transformer and its insulation breakdown. The last one leads to transformer failure. The LoL constraint ensures that transformer HST will not cause an accelerated insulation ageing which could lead to early transformer failure.

METHODOLOGY

DSO has strict requirements for methodology. Therefore, the proposed approach must guarantee that transformer will not have unacceptable overloading (unacceptable HST_{max} and LoL) in N-1 mode due to calculated reserve interconnection.

This transformer overloading could be caused by underestimation of input data – actual ambient temperature and/or irregularity of load profile. Therefore, it is necessary to ensure that reference input data (ambient temperature and load profile), used for reserve determination, have enough margin over their real values. To achieve this goal, in this section we present the approach for ambient temperature consideration and the approach for consideration of new consumer load profile. In addition, we present the algorithm to define admissible power reserve for congested primary substation with consideration of transformer HST and LoL and its input data uncertainty.

Consideration of ambient temperature uncertainty

The ambient temperature has a strong impact on admissible transformer loading. Thus, it is necessary to consider the annual variation of ambient temperature for reserve estimation.

The goal of this section is to present the robust and simple approach for consideration of annual ambient temperature. To achieve this goal, we propose to use worse (the highest) historical ambient temperature at each month as reference value over the month duration. This approach allows obtaining the worse HST and LoL of power transformer with regard to ambient temperature variations during a year.

As initial data for worse ambient temperature calculations, we use the hour ambient temperatures for the last 30 years (Figure 1), taken from [5].

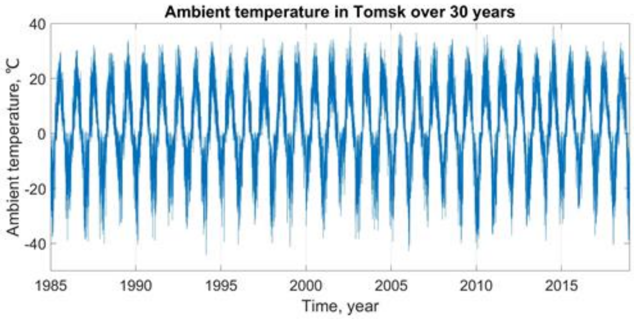

Figure 1 – Historical ambient temperature over 30 years in Tomsk (Siberia, Russia)

After the analysis of historical data, we could build the probability density function (PDF) of ambient temperatures for each month. (Figure 2 below)

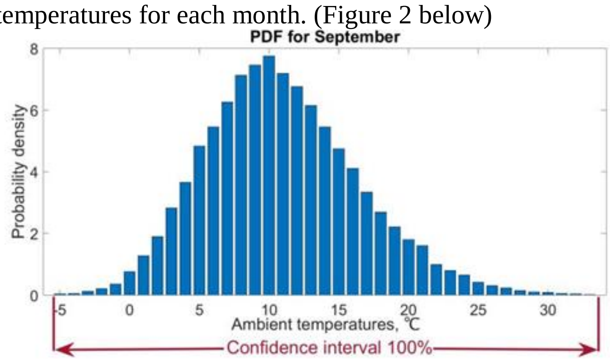

Figure 2 – Probability density function with confidence interval 100% for September in Tomsk (Siberia, Russia)

To choose worse ambient temperature, we propose to apply confidence interval 100% for given PDF. As alternative, we could use other confidence intervals – 99%, 95% or 90%. Thus, within chosen confidence interval we could define the highest ambient temperature. In Figure 2, the highest ambient temperature within confidence interval 100% is +33℃.

Figure 3 below presents the highest ambient temperatures for each month obtained in similar way. Figure 3 will be used as reference ambient temperature in transformer thermal model for HST and LoL calculation.

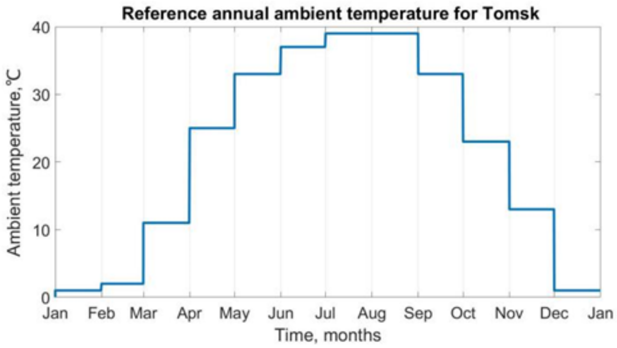

Figure 3 – The graph with the highest ambient temperature at each month in Tomsk (Siberia, Russia)

The advantages of proposed approach for ambient temperature consideration are following:

1. Due to worse ambient temperature choice as constant value over whole month duration, we take into account variable nature of ambient temperature. Therefore, we minimize the negative effect in case of real ambient temperature higher than reference value. It is explained that the real ambient temperature rises over such reference value (worse ambient temperature) will last most probable only for short time. Thus, corresponding negative effect will be negligible in comparison with the effect of using worse ambient temperature over whole duration of month. Consequently, we could minimize ambient temperature uncertainty impact on HST and LoL of transformer.
2. It is possible to make the calculation of worse ambient temperature graph (as in Figure 3) only once for the scale of city or even a region. Thus, such graph could be used for all primary substations located at considered territory. If new ambient temperature maximums appear, we could easily correct graph.
3. The use of different confidence intervals (100%, 99%, 95% or 90%) allows DSO more flexible choice of reference ambient temperature with regard to benefit/risk assessment and thus to define corresponding reserve for congested primary substation.

Consideration of new consumer load profile uncertainty

The annual load profile of new consumers could have various irregularity (shape). These irregularities could not be accurately defined at the stage of reserve determination. Thus, load profile of primary substation after new load interconnection could not be accurately determined too. Consequently, HST and LoL values are uncertain. This uncertainty makes difficult to define the admissible reserve of primary substation through thermal modelling.

Thus, the goal of this section is to present the robust and simple approach to consider all possible load profile irregularities of new consumers. To achieve this goal, we propose to use a constant load profile, defined by its peak load, as reference load profile of new consumer. Such assumption allows obtaining the worse HST and LoL with regard to any other load profiles with equal peak load. Based on worse case, the admissible reserve is defined.

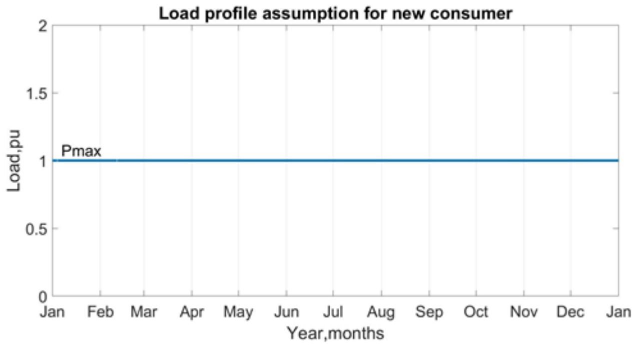

Figure 4 – Annual constant load profile of new consumer as assumption for thermal modelling

The advantages of proposed approach for load profile consideration of new consumers are following:

1. The proposed consideration could be easily adapted to practice since the existing application for distribution network interconnection has the information about peak load of new consumer. Thus, it is sufficient condition (together with reference ambient temperature and initial load profile of substation) to estimate the worse HST_{max} and LoL of transformer.

2. Constant load profile of new customer, used in thermal modelling, could guarantee that obtained transformer annual HST and LoL will be the worse in comparison with HST and LoL of any other load profiles with same peak load.

Algorithm for substation reserve determination

The goal of this section is to present the algorithm for reserve determination with HST_{max} and LoL consideration:

Step 1 Prepare initial load profile and reference ambient temperature.

Step 2 Estimate preliminary reserve as difference between peak load and transformer loading, corrected to ambient temperature during a peak

Step 3 Increase the initial load profile by reserve value

Step 4 Calculate HST_{max} and LoL after adding of preliminary reserve

Step 5 If HST_{max} > 120 *and/or* LoL > 8760 then
Preliminary reserve is overestimated.
Decreasing the reserve value:
While HST_{max} > 120 and/or LoL > 8760
(a) Decrease reserve by 1 %
(b) Add reserve value as constant load profile to initial load profile of primary substation
(c) Calculate HST_{max} and LoL
Otherwise finish
If HST_{max} < 120 *and* LoL < 8760 then
Preliminary reserve is underestimated.
Increasing the reserve value:
While HST_{max} < 120 and LoL < 8760
(a) Increase reserve by 1 %
(b) Add reserve value as constant load profile to initial load profile of primary substation
(c) Calculate HST_{max} and LoL
Otherwise finish

CASE STUDY

Initial data

To verify the DTR-based approach, we compare its results with analogical results, obtained by conventional DSO approach. As case study, we consider the real congested primary substation with two power transformers 25 000 kVA ONAF, located in Tomsk.

The transformer parameters, used in thermal modelling, are taken from [6] and presented in Table 1 below.

Table 1 – Transformer thermal parameters

Parameter	Value	Parameter	Value
x	0.8	$\Delta\theta$hr	26
y	1.3	$\Delta\theta$or	52
R	6	k11	0.5
τo	150	k21	2
τw	7	k22	2

The initial load profile of primary substation (in p.u. of transformer nominal rating) and reference ambient temperature graph are presented in Figure 5. Reference ambient temperature graph for Tomsk is taken from Figure 3. Initial load profile represents load profile where for each time step the corresponding load value is maximum among measured load for the last 5 years.

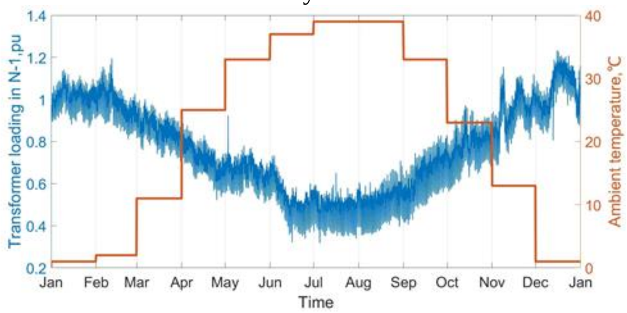

Figure 5 – Initial load profile of primary substation and reference ambient temperature graph in Tomsk

Substation reserve without transformer HST and LoL consideration – conventional approach

The conventional approach determines the reserve as difference between the lowest transformer capacity in N-1 mode (in this case S_{N-1} = 1 p.u. = 25 000 kVA) and peak load of primary substation (according to Figure 5, $S_{load\ max}$ = 1.2344 p.u.)

$$Reserve\ = S_{N-1} - S_{Load\ max} = 1 - 1.2344$$
$$Reserve = -0.2344\ p.u. = -5\ 860\ kVA$$

According to conventional (no-DTR) approach there is no reserve at this primary substation. Thus, load interconnection is restricted. Moreover, the reserve is negative (- 5680 kVA). It means that power supply capability of given primary substation could be limited for almost 6 MVA of existing consumers in N-1 mode. Therefore, it implies DSO to plan the large capital expenditures for reinforcement of two 25 000 kVA transformers at this primary substation.

Substation reserve with transformer HST and LoL consideration – DTR-based approach

To estimate proposed (DTR-based) approach, we determine the reserve of above-considered primary substation with consideration of transformer HST_{max} and LoL in N-1 mode. To achieve this goal, we use the suggested algorithm.

At step 1-2 of algorithm, we preliminarily estimate the transformer reserve, corresponding to the difference between load maximum and admissible transformer loading, corrected to ambient temperature. The calculation results of these parameters are presented in Table 2 below:

Table 2 – The algorithm results at step 1-2

$S_{load\ max}$	$T_{amb\ Sloadmax}$	$S_{admissible}$	Reserve
1,234 p.u.	+1 °C	1,317 p.u.	0,083 p.u.

At step 3 of algorithm, we increase all values of load profile (Figure 6) on reserve value (0.083 p.u.), calculated at previous step. In other words, we add constant load profile, defined by this reserve value, to initial load profile.

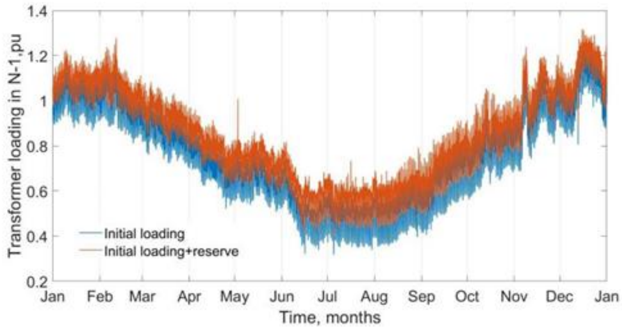

Figure 6 – Initial load profile (blue) and the same load profile after adding reserve (orange)

Further, at step 4 of algorithm, we estimate the transformer HST_{max} and LoL for new load profile (orange in Figure 6) and reference ambient temperature. Figure 7 below represents the obtained HST of transformer windings over year and corresponding loss of insulation life by the end of year.

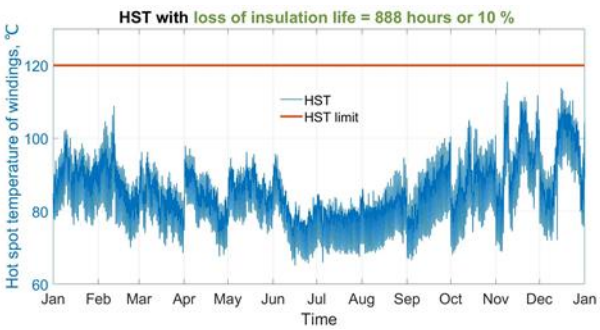

Figure 7 – HST plot and corresponding LoL

The results for preliminary reserve value show that transformer HST and LoL do not exceed their permissible values:

$$HST_{max} = 115{,}5\ °C \leq 120\ °C$$
$$LoL = 888\ hours \leq 8\ 760\ hours$$

From obtained HST_{max} and LoL, it could be seen that there is still margin between HST and HST limit as well as between LoL and LoL limit. Thus, these margins could be used for additional reserve interconnection.

Therefore, we should optimize the reserve value (step 5 of algorithm). To achieve this goal, we increase the reserve by 0.01 p.u. until HST_{max} and/or LoL will be reached. After three iterations, the constraint – HST_{max} reaches its permissible value:

$$HST_{max} = 119\ °C \leq 120\ °C$$
$$LoL = 1\ 259\ hours \leq 8\ 760\ hours$$

The other constraint - LoL is less than 15% from its permissible limit. Consequently, the transformer operates within all admissible thermal constraints. Therefore, the substation reserve is increased from 0.083 p.u. to 0.113 p.u. Thus, the given congested primary substation could safely interconnect 2825 kVA (0.113·25 000) of new consumer load with any load profile.

CONCLUSION

The paper presents the DTR-based approach, considering the uncertainties of ambient temperature and load profile of new consumers, for reserve determination at congested primary substation. The consideration of ambient temperature and load uncertainty is done by assuming their worse values. Thus, reserve value, obtained for such worse conditions, could be safely interconnected to primary substation.

The case study shows that proposed approach allows the safe interconnection for 2825 kVA of new consumers to real primary substation whereas conventional approach restricts any load interconnection. Moreover, according to convention approach, the primary substation capacity lacks 5 860 kVA for reliable power supply of existing consumers in N-1 mode.

Thus, the proposed approach could allow more load to be interconnected to existing primary substation. Consequently, the investments in transformer reinforcement, forced by load growth, could be deferred.

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