Loading Capacity of Standard Oil Transformers on Photovoltaic Load Profiles

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Abstract

Oil immersed distribution transformers are widely used in public networks. The rating is optimized for the known load profile. The increasing infeed of distributed generation in the networks, esp. by photovoltaic(PV)-generators, leads to modified loading profiles. For the investigation of the capacity of distribution networks to cope with fluctuating distributed generation, the loading capacity of the transformers under these conditions is a point of interest. This paper describes a simulation model to calculate temperature and ageing according to the Standard DIN-EN 40076-7 [1]. Parameter studies with measured PV-infeed and ambient temperature profiles were carried out. Indoor and outdoor disposition is considered. The influence of user-load together with PV-generation is analyzed. The results indicate that a PV-power of 1.5 times the rated power of the transformer neither leads to overheating nor to unacceptable ageing of the transformer. All values are covered by the recommendations for cyclic loading given in the Standard.

1 Introduction

Due to many reasons, such as CO_2-issue, governmental promotion and substancially rising prices of oil and other fossil energy sources, an increase in dispersed electric power generation can be noticed. Therefore the impact of PV-generators in the public low voltage grid emerges as a matter of interest for the local network operators concerning system overloading. One question is the behavior and/or limitation of standard oil immersed distribution net transformers to a typical PV-generated fluctuating load profile.

At present the rated values of these transformers refer to a continuous load at an ambient temperature of 40°C.

2 State of the Art

Distribution transformers are widely standardized. The key data is described in DIN – 42 500 [2]. The typical units used in German distribution grids are 100, 120, 250, 400 and 630 kVA transformers [3]. In residential areas the transformer type is selected assuming a maximum load estimation depending on the type (grade of electrification) and the number of households which are supplied [4]. Those networks were only designed for energy consumption. The increasing infeed by PV-power plants leads to a partial inversion of the transformer-loadflow in the distribution grids. Due to undetermined behavior of distribution transformers in case of fluctuating power flow the rated power of the transformer was set to limit the PV-infeed. Studies to determine the maximum capacity of low voltage grids for PV-infeed [5] show that for a voltage limitation of ± 10 % U_N (network nominal voltage $U_N = 400$ V, 50 Hz) the rated transformer power is the main bottleneck.

3 Simulation Model

To test the impact of PV-load profiles on a transformer a thermal model according to DIN-EN 40076-7 [1] has been set up. The differential equations solution was used (see Fig. 1). Input parameters are the load factor K (load current / rated current) and the ambient temperature Θ_a. The model calculates the oil- and hotspot temperature (Θ_o, Θ_h). The relative ageing-rate V is calculated according to Eq. 1 for non-thermal upgraded paper.

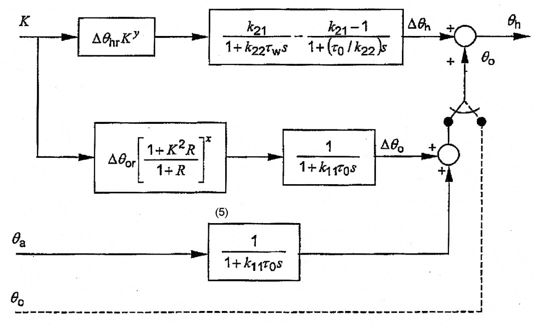

Fig. 1 Block diagram representation of the thermal transformer model [1]

$$V = 2^{(\Theta_h - 98)/6} \qquad \text{Eq. 1}$$

The investigated transformer was a 20/0.4 kV, 400 kVA, $u_K = 4\%$ ONAN type. The relevant model parameters R, k_{11}, k_{12}, k_{22} and the time constants τ_W and τ_O were calculated according to the Standard based on a manufacturer's temperature rise run and the data sheet. The model was implemented as a script in a commercial network analysis program. The modeling was verified with the dynamic load profiles given by the Standard, with load step responses and a measured temperature rise run. The maximum divergence between the simulated temperature rise run and the measured data was below 3 K (Fig. 2). The verified model is based on an outdoor disposition of the transformer. For simulations of transformers with enclosure (Kiosk) a temperature correction of 15 K was used as defined in the Standard.

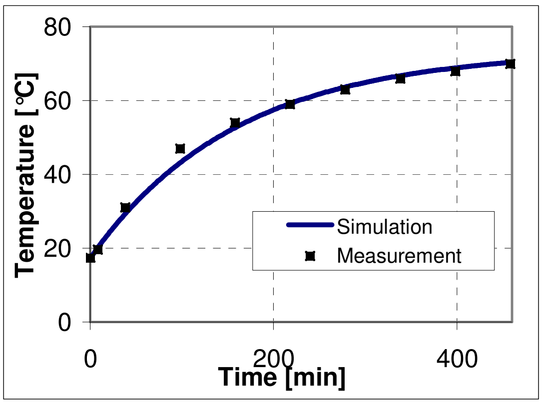

Fig. 2: Simulated and measured top-oil temperature of the temperature rise run

A long term measurement of the AC-power-output of the inverter of a 1 MW photovoltaic power plant located in Munich [6] together with the ambient temperature were used to simulate the PV–infeed. The time resolution of the data was 1 min (mean values). Taking into account the hot spot time constant of the transformer of about 4 min a simulation time step of 1 min is sufficient [1]. The measured and simulated time period was the complete year 2005. The energy-yield with 950 kWh/kWp of the PV-plant was slightly below average in relation to other years. Therefore the transformers temperatures and ageing might be slightly higher in other years. To model PV-generators with a different rated power the measured AC-power-output was linearly scaled. Symmetric loading was assumed. The power factor was set to cos(φ) = 1.0. As the effect of harmonics on transformer temperatures is not covered by the Standard this influence was neglected.

To investigate the impact of the user load the 15 min. average VDEW standard load profile for households was taken into account. The 1 min values were linearly interpolated to the simulation time step of 1 min. An annually energy consumption of 4500 kWh/a per household (4 persons.) was assumed [7].

The VDEW standard load profile describes the average user load of many households. Because the load fluctuation increases with fewer households the use of the load profile is restricted to networks with more than 150 households [8] But even with less than 150 households the simulations are a good indication for the temperatures to be expected because the effects of a more dynamic load profile are dampened by the thermal time constants of the transformer.

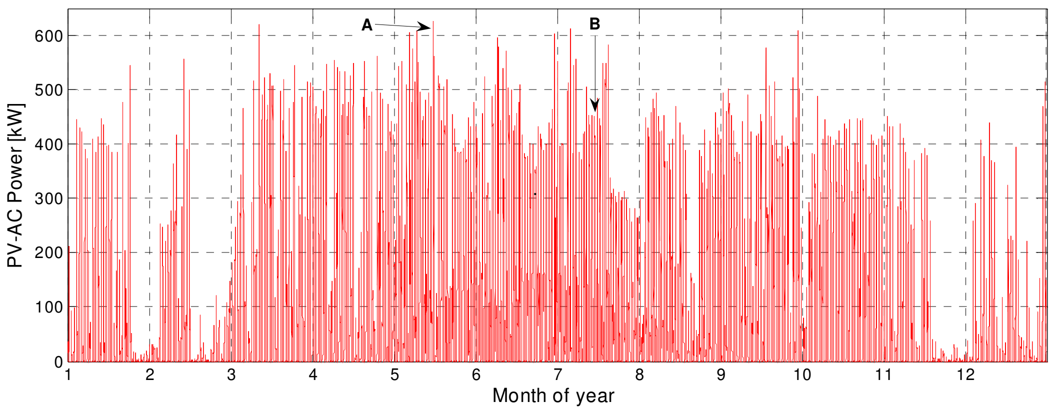

Fig. 3 PV-infeed / transformer load in 2005; (PR = 1.5; LR = 0)
Mark A: max power peak; Mark B: max hotspot temperature

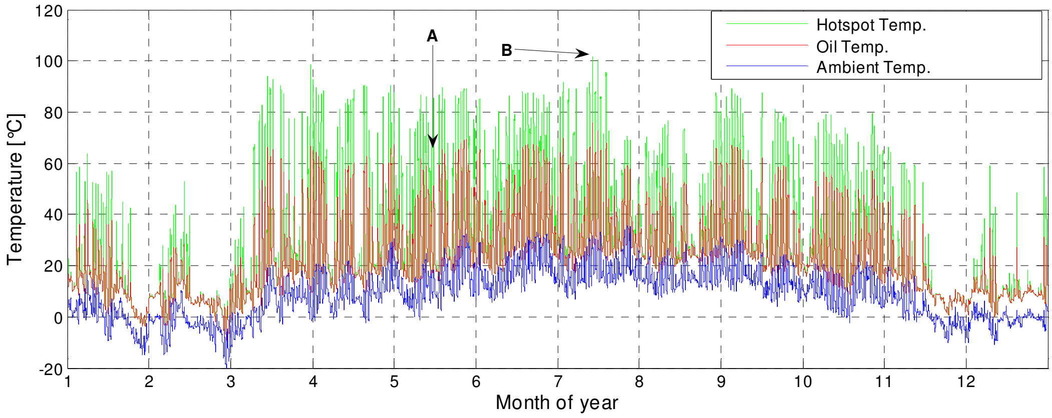

Fig. 4 Measured and simulated temperatures; (PR = 1.5; LR = 0)
Mark A: max power peak; Mark B: max hotspot temperature

4 Simulation Results

In order to investigate the impact of different loading of the transformer on the hot-spot and oil temperature as well as on the ageing the power ratio PR and the load ratio LR were defined:

$$PR = \frac{rated\ \ power\ \ of\ \ PV - plant}{rated\ \ power\ \ of\ \ transformer} \qquad \text{Eq. 2}$$

$$LR = number\ \ of\ \ households \cdot loadprofile \qquad \text{Eq. 3}$$

Parameter studies for PR = 0.5 – 2.25, LR = 0 - 330 and indoor and outdoor disposition were conducted. For every parameter combination a simulation for the whole year 2005 was performed.
Due to the simple consideration of the housing defined by the Standard the results with housing mainly show a temperature offset compared to the results without housing. The temperature behavior versus time and the resulting ageing differ only marginally. As the main point of interest is the maximum loading capacity the results are discussed only for indoor disposition.

Loading Capacity with PV-Load only

Fig. 3 gives the the PV-generator output respectively the transformer current for a power ratio PR = 1.5. The measured ambient temperature together with the calculated oil and hotspot temperature for the investigated transformer is shown in Fig. 4.

Fig. 3 indicates that the maximum power is fed in only on few days of the year. The efficiency of the PV-generator depends on the ambient temperature. This effect leads to significantly reduced power generation on sunny days because the temperature of the PV-cell is much higher than the nominal temperature of 20°C, which is used to determine the nominal power output of the cell [9]. Therefore, the maximum power output of the PV-generator occurs on rather cool days in spring and autumn and especially when moving clouds are causing high gradients of solar radiation on the cells. This behavior is advantageous for the transformer loading capacity because the peak power is generated only for a short period of time.

Fig. 4 shows, that the hotspot-temperature almost always stays below 100° C, although the ambient temperature changes significantly with the seasons. This is caused by the fact, that especially on days with a high ambient temperature, when the transformer loading capacity is the limited, the PV-generators efficiency is reduced too.

The maximum hotspot temperature is reached at a quite low PV-generator output of about 75 % of the nominal power (Fig. 5 and Fig. 6). The temperature peak of oil and hotspot is caused by the high ambient temperature of about 35°C and the continuous transformer loading.

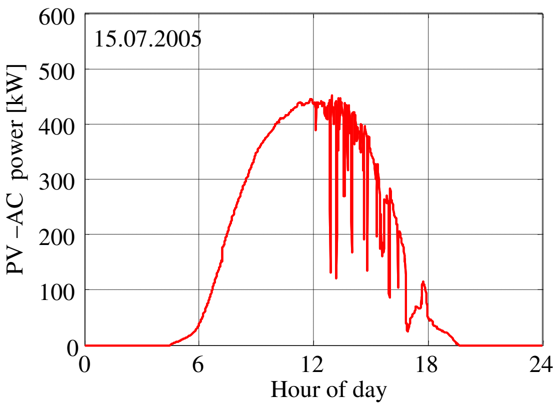

Fig. 5 Transformer load on the day with the maximum hotspot temperature (PR=1.5; LR=0).

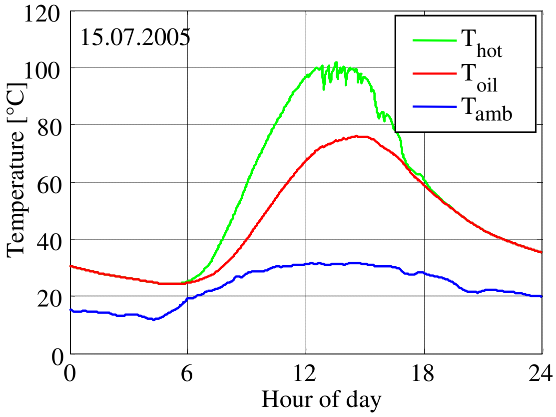

Fig. 6: Temperatures on the day with the maximum hotspot temperature (PR = 1.5; LR = 0).

The day of the maximum power output of the PV-generator is shown in Fig. 7 and Fig. 8. The low ambient temperature and highly fluctuating radiation leads to high power peaks. On the other hand, the low ambient temperature and the dampening of the fluctuations by the transformers thermal time constants are limiting the transformer hotspot and especially oil temperature on this day.

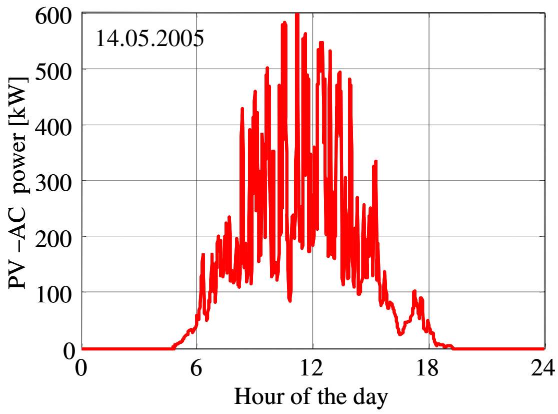

Fig. 7: Transformer load on the day of the maximum PV-Power peak (PR = 1.5; LR = 0)

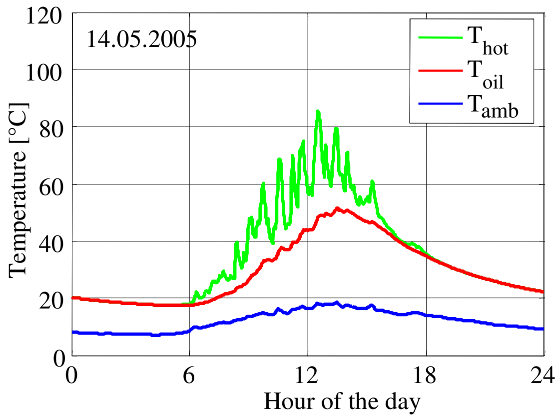

Fig. 8: Temperatures on the day with the maximum PV-Power peak (PR = 1.5; LR = 0).

To evaluate the maximum loading capacity for a cyclic loading of the transformer the Standard mentions different criteria to meet.

- The hotspot temperature of 120°C should not be exceeded.
- The oil temperature should not exceed 105°C.
- To limit overheating on bushings and cable-end connections and other devices the current should be restricted to 1.5 times the rated current.

Apart from this the cumulated ageing should not exceed 360 days per year to ensure the expected lifetime.

For that reason for every parameter set the maximum oil and hotspot temperature and the cumulated ageing in the simulation period were determined.
The results for in- and outdoor disposition are shown in Fig. 9 to Fig. 11:

- hotspot temperature limit of 120°C is reached at PR ~ 1.75.
- oil temperature of 105°C is reached at higher values of PR (>2) because of the high thermal oil time constant (~180 min) compared to the short load periods, even on sunny days
- ageing is of lower relevance because of low average load and ambient temperature compared to the transformer design (recommendation is exceeded at PR > 2)

The difference for indoor and outdoor disposition leads to slightly higher temperatures and increased ageing for PR < 1.75.

The simulation results indicate that the decisive criterion for the loading capacity of an oil immersed distribution transformer in case of PV-power infeed is the limitation of the current to 1.5 times the rated current. Therefore the power ratio PR is limited to 1.5.

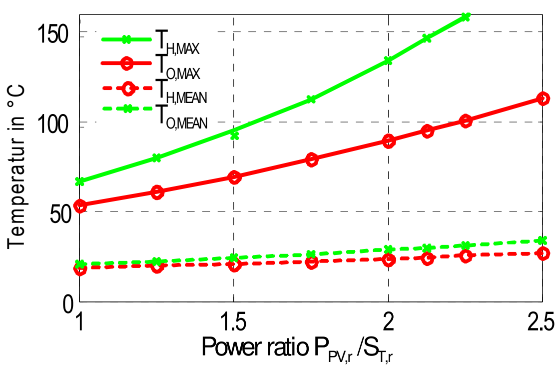

Fig. 9: Transformer temperatures on PV-infeed for outdoor disposition without user load.

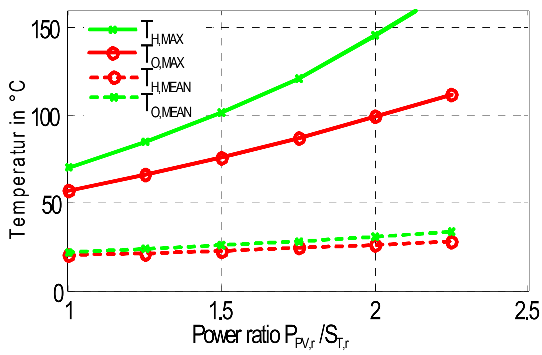

Fig. 10: Transformer temperatures on PV-infeed for indoor disposition without user load.

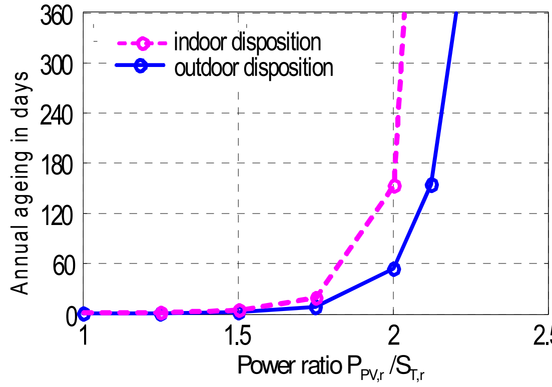

Fig. 11: Cumulated annual transformer ageing for indoor and outdoor disposition on PV-infeed without user load.

Effects of additional user load

In distribution network transformer stations the PV-infeed is usually combined with the user load. This leads to lower power peaks due to the compensation of generation and consumption in the low voltage grid. Therefore, lower temperatures are to be expected. On the other hand the overnight consumption increases the utilization of the transformer and interferes with the nightly cool down of the transformer. To investigate these effects, simulations with additional user load were performed. All simulations show that, - compared to exclusive load or PV-infeed - the combination of both reduces the temperatures and ageing. This effect can be visualized best with a high user load eg. LR = 330 (Fig. 12 and Fig. 13).

It can be concluded, that the worst case for a transformer is loading with PV-generation only. Therefore a limitation of PR = 1.5 even with user load is a conservative estimation.

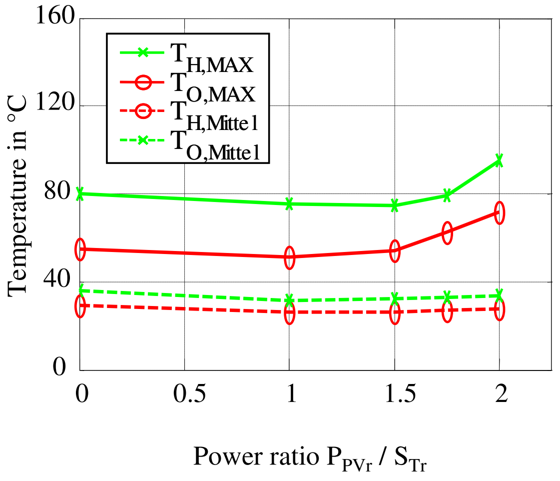

Fig. 12: Transformer temperatures on PV-infeed and a user load of 330 households (indoor disposition)

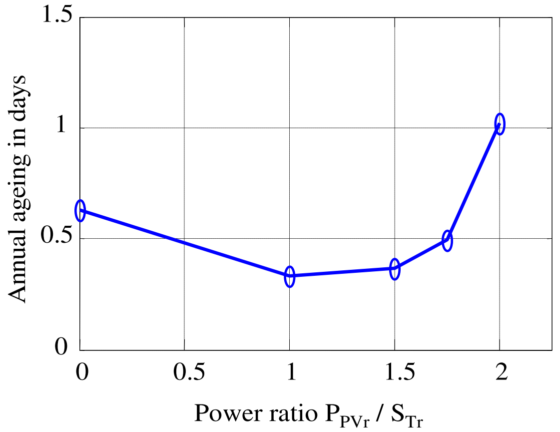

Fig. 13: Cumulated annual ageing on PV-infeed and a user load of 330 households (indoor disposition)

5 Conclusion

The maximum loading capacity for an oil-immersed distribution transformer was determined by means of simulation based on measurements of PV-infeed and ambient temperature during one whole year (2005). The effect of additional user load and transformer housing was considered.

It is shown that a 400 kVA oil immersed transformer in indoor disposition does not overheat with a PV power ratio (rated PV-inverter power by rated transformer power) below 1.75. Additional consumption increases the maximum loading capacity of the transformer.

According to DIN-EN 40076-7 [1] a current greater than 1.5 times the nominal current should not be used for cyclic loading because other components of the transformer station such as bushings or cable-end terminations could be overloaded.

With a specification of a maximum PV-inverter power of 1.5 times the transformer rated power (PR = 1.5), safe operation of a transformer is given.

The marginal overloading capability of PV-inverters ensures a current within the acceptable range for cyclic loading. By neglecting the influence of the user load, an additional security margin is available. The influence of annual fluctuations on ambient temperature and energy-yield is covered by the uncritical transformer temperature and ageing at PR = 1.5.

Smaller transformers should be even more tolerant to PV-load profiles, because they are less vulnerable to loading beyond the nameplate rating.

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