SIEMENS

Totally Integrated Power

Technical Series, Edition 16

Transformer Selection according to Utilisation Profiles

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1. Regulations concerning efficiency requirements of dry-type transformers

In June 2014, Regulation No. 548/2014 issued by the EU Commission [1] has become effective. This regulation describes the ecodesign requirements of power transformers which have been placed on the market after 01 July 2015 and have been, or will be commissioned on/after that date. It applies to transformers with a minimum rating of 1 kVA. In addition, this regulation also refers to the second level of efficiency improvements and loss reductions, respectively, for marketing transformers which shall be effective as of 01 July 2021.

The requirements described therein include the determination of the maximum limits for short-circuit losses and no-load losses or the minimum value for the maximum transformer efficiency. The reduction of transformer losses shall reduce the annual CO_2 emissions during operation. Thus, the regulation prescribes the state of the art which has been established by the international standard IEC 60076-20 (VDE 0532-76-20). Currently, the standard is in the Draft state.
Section 6.3.2 of the standard specifies the maximum permissible loss values for dry-type transformers (Tab. 1). In this context, a distinction is made between basic energy efficiency (performance level 1, in the following abbreviated as EEF1) and high energy efficiency (performance level 2, in the following abbreviated as EEF2). Basically, load loss is reduced by 10 % in EEF2. For transformers featuring a rating below 800 kVA also applies that their no-losses are reduced in level EEF2. In compliance with the Ecodesign Regulation No. 548/2014, only level EEF 2 transformers may be placed on the EU market as of 01 July 2021.

Note: In this context, the term "efficiency" is used as the ratio of apparent output power to apparent input power.

Tab. 1: Loss data for the energy performance levels (EEF) of dry-type transformers in compliance with IEC 60076-20 (VDE 0532-76-20)

Transformer rating S_r	EEF1		EEF2	
	Load losses P_k	No-load losses P_0	Load losses P_k	No-load losses P_0
630 kVA	7.6 kW	1.1 kW	7.1 kW	0.99 kW
800 kVA	8 kW	1.3 kW	8 kW	1.17 kW
1,000 kVA	9 kW	1.55 kW	9 kW	1.395 kW
1,250 kVA	11 kW	1.8 kW	11 kW	1.62 kW
1,600 kVA	13 kW	2.2 kW	13 kW	1.98 kW
2,000 kVA	16 kW	2.6 kW	16 kW	2.34 kW
2,500 kVA	19 kW	3.1 kW	19 kW	2.79 kW
3,150 kVA	22 kW	3.8 kW	22 kW	3.42 kW

2. Energy efficiency management

Loss and efficiency are product- or system-specific characteristics which apply for a specific operating condition (usually the normal condition). In other operating conditions, losses and efficiency levels are dependent on these operating conditions. This means that efficiency evaluations during planning phases are only possible if concrete assumptions have already been made concerning the operating conditions. The selection of an efficient transformer considers both its specific characteristics (load-dependent efficiency data) and its normal operating load (load profile).

IEC 60364-8-1 (VDE 0100-801: Low-voltage electrical installations – Part 8-1: Energy efficiency) explicitly points to the load dependency of a transformer's efficiency. This also means that the environmental impact of transformers depend on the operating point and the load-loss correlation.

The total power loss (P_V) in operation is calculated from the sum of no-load losses and load losses under a specific load (S_{Load}). No-load losses are load-independent. They are generated as soon as a voltage is applied to one of the transformer windings (primary or secondary side). Whereas load losses are dependent on the square loading ratio (S_{Load} / S_r)^2 and the loss values P_k (see Table 1). The loading ratio is the ratio of apparent load power (S_{Load}) to the rated apparent power (S_r) of the transformer.

$$P_V = P_0 + \left(\frac{S_{Load}}{S_r}\right)^2 \cdot P_k$$

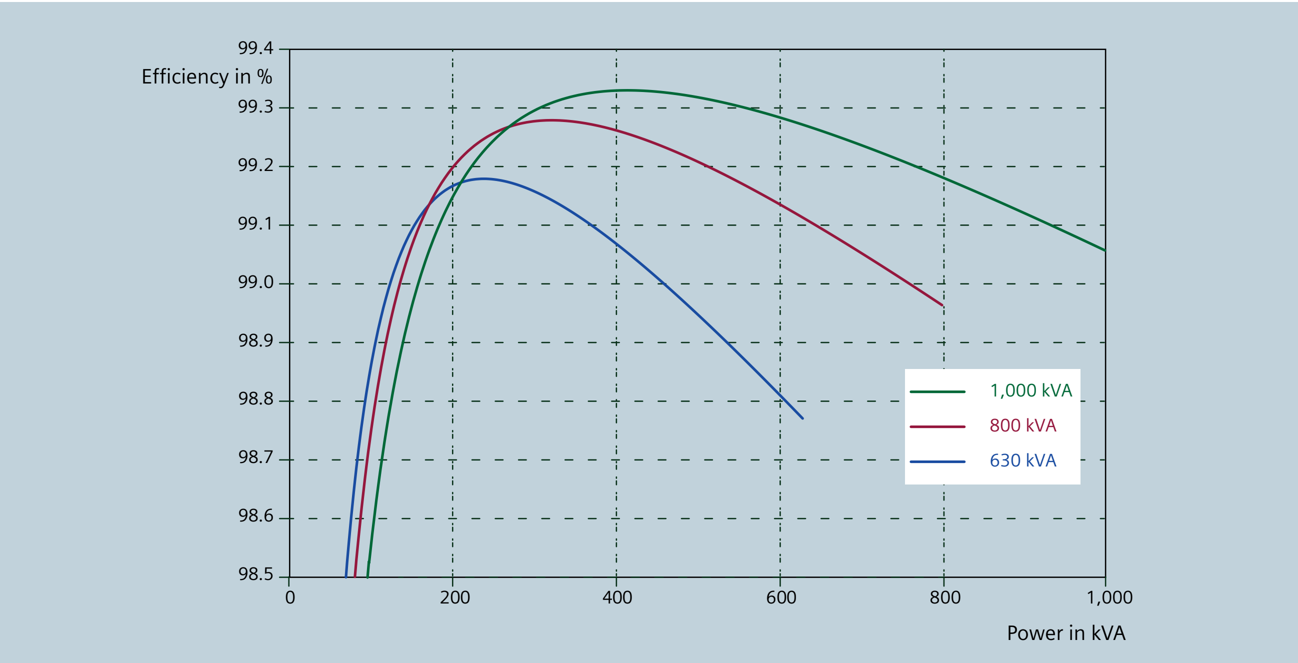
A loss minimum is attained if the no-load loss equals the load loss. Hence, the so-called load factor k provides the optimal operating points as listed in Tab. 2 (and Fig. 1) ($k \cdot S_r$) showing the maximum efficiency.

$$k = \sqrt{\frac{P_0}{P_k}}$$

Tab. 2: Operating points of EEF1 dry-type transformers in compliance with IEC 60076-20 (VDE 0532-76-20)

S_r	Load factor k	$k \cdot S_r$
630 kVA	38.044%	239.7 kVA
800 kVA	40.311 %	322.5 kVA
1,000 kVA	41.500 %	415.0 kVA
1,250 kVA	40.452 %	505.6 kVA
1600 kVA	41.138 %	658.2 kVA
2,000 kVA	40.311 %	806.2 kVA
2,500 kVA	40.393 %	1,009.8 kVA
3,150 kVA	41.560 %	1,309.1 kVA

Fig. 1: Efficiency curves for current EEF1 transformer types with 630, 800 and 1,000 kVA from Tab. 2



3 Load and utilisation profiles

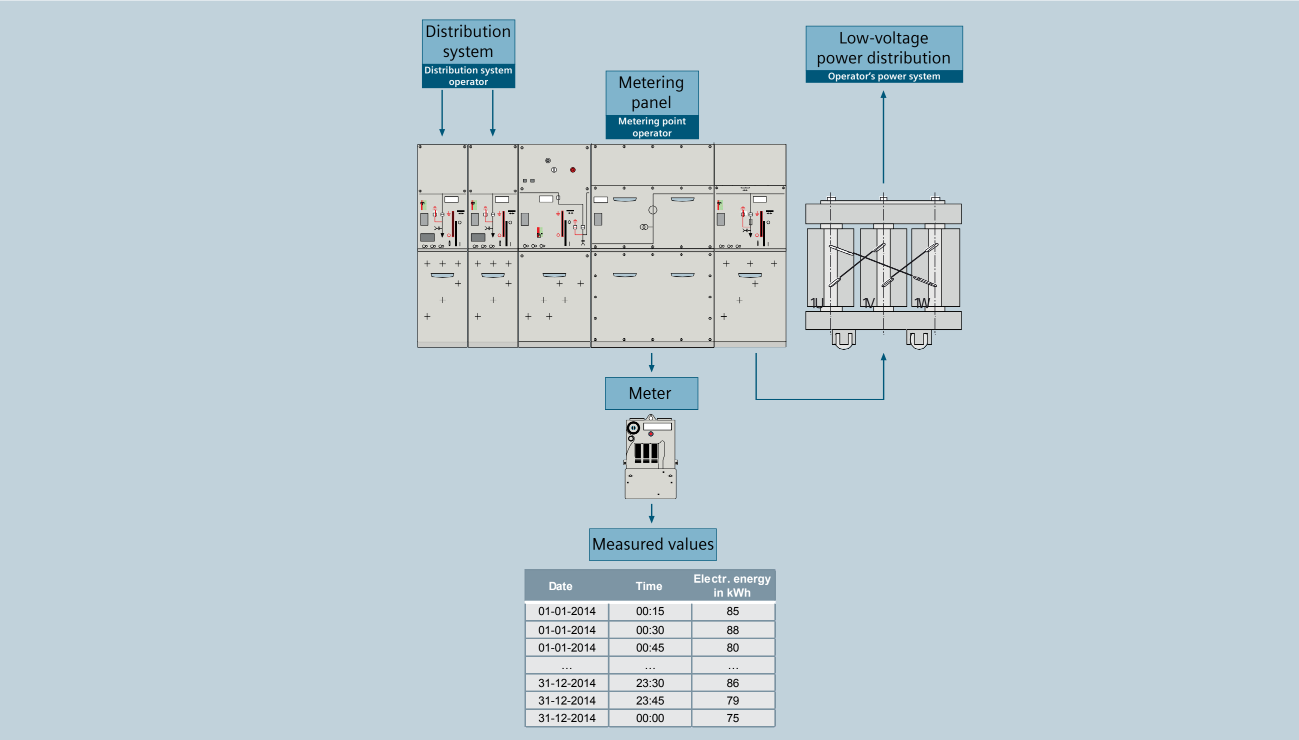
Buildings such as office towers, hotels, hospitals, and data centres often need connected loads which cannot be provided from the low-voltage power system. In accordance with the technical supply conditions of the local distribution system operator (DSO), these buildings are supplied from the medium-voltage grid.

The consumer substation usually includes a metering panel. It serves for energy cost billing. The electric energy drawn from distribution system is measured at 15-minute intervals (Fig. 2). The measurement data can be made available to the customer (in many cases only upon request).

The 15-minute measurands serve as a basis for the representation of load and utilisation profiles (Fig. 3). For the load profile, the 15-minute values of the energy procured (respectively the mean power for the 15-minute interval) is plotted over a period of typically one year: The X-axis shows the time and the Y-axis the electric energy or power.

A utilisation profile can be interpreted as the graphical evaluation of the load profile. Plotted are the load hours of one year added up (Y-axis) assigned to a specific value of transmitted power (X-axis). Owing to the time correlation, the load profile allows to identify a trend or temporal development, i.e. the power procured over time, an information which cannot be derived from the utilisation profile any more. Instead, the utilisation profile highlights the correlation between the amount of power purchased and the operating time over the period considered.

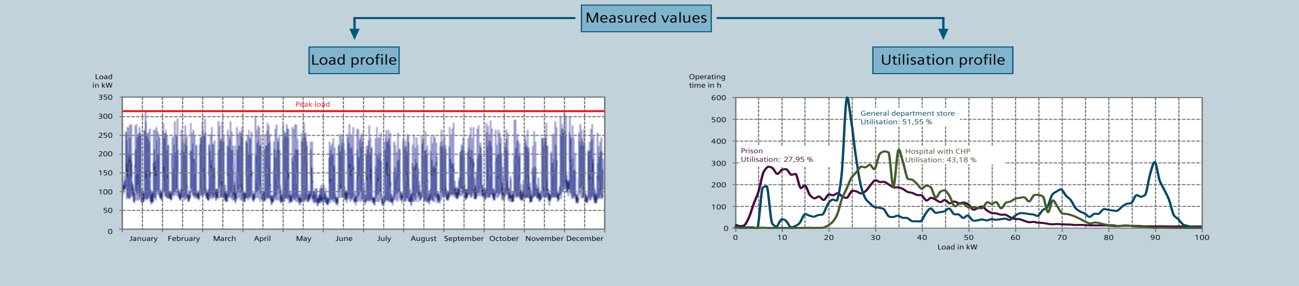
Fig. 2: Medium-voltage connection and metering at the point of common coupling



Date	Time	Electr. energy in kWh
01-01-2014	00:15	85
01-01-2014	00:30	88
01-01-2014	00:45	80
…	…	…
31-12-2014	23:30	86
31-12-2014	23:45	79
31-12-2014	00:00	75

Fig. 3: Creation of load and utilisation profiles from the measurement data

Date	Time	Electr. energy in kWh
01-01-2014	00:15	85
01-01-2014	00:30	88
01-01-2014	00:45	80
…	…	…
31-12-2014	23:30	86
31-12-2014	23:45	79
31-12-2014	00:00	75



The utilisation profile directly supplies the data for determining transformer loss and teh corresponding loss energy (power and corresponding hours).

The operating time is defined as the quotient of the measured electric energy to the peak power:

$$\text{Operating time (in h)} = \frac{\text{Electric energy (in kVAh)}}{\text{Peak power (in kVA)}}$$

It specifies how long the peak power must theoretically be applied in order to transmit the energy over the entire period considered. Comparably, a mean load (annual averaged apparent operating power) can be specified over the period considered (8,760 hours yearly):

$$\text{Mean load (in kVA)} = \frac{\text{Electric energy (in kVAh)}}{\text{8,760 h}}$$

So that the load factor a is defined as follows:

$$\text{Load factor a} = \frac{\text{Mean load}}{\text{Nominal apparent power}}$$

4. Transformer energy losses

From the load profile and utilisation profile, respectively, it becomes evident that transformers are not only operated in the operating point showing the highest efficiency. Accordingly, operating losses depend both on the efficiency curve (Fig. 2) and the load or utilisation profile of the loads supplied. In Fig. 4 and Fig. 5, the efficiency curves (transformer outputs of 630 kVA to 2,000 kVA) are overlaid with two utilisation profiles:

a) Utilisation profile for a hospital with 450 beds and a peak power demand of approx. 610 kVA
b) Utilisation profile for a metered commercial enterprise with a quite considerable proportion of power demand for continuous cooling and a peak power demand of approx. 610 kVA.

Attention must be paid to the width of value ranges for efficiency and load duration (tolerance band). The most favourable transformer operating range is limited by a +/- 20 % interval for load near the operating point (interval boundaries are marked by triangles and circles for each curve). For the hospital's utilisation profile in Fig. 4, the mean load is within the highlighted operating range of the 630-kVA transformers and just about within the range of 800-kVA transformers. For the commercial enterprise in Fig. 5 with its higher mean load, the efficiency curves of the larger 1,000-kVA and 1,250-kVA transformers are more favourable.

Fig. 4: Utilisation profile of a hospital and comparison of efficiency curves of several transformers in compliance with IEC 60076-20 (VDE 0532-76-20)

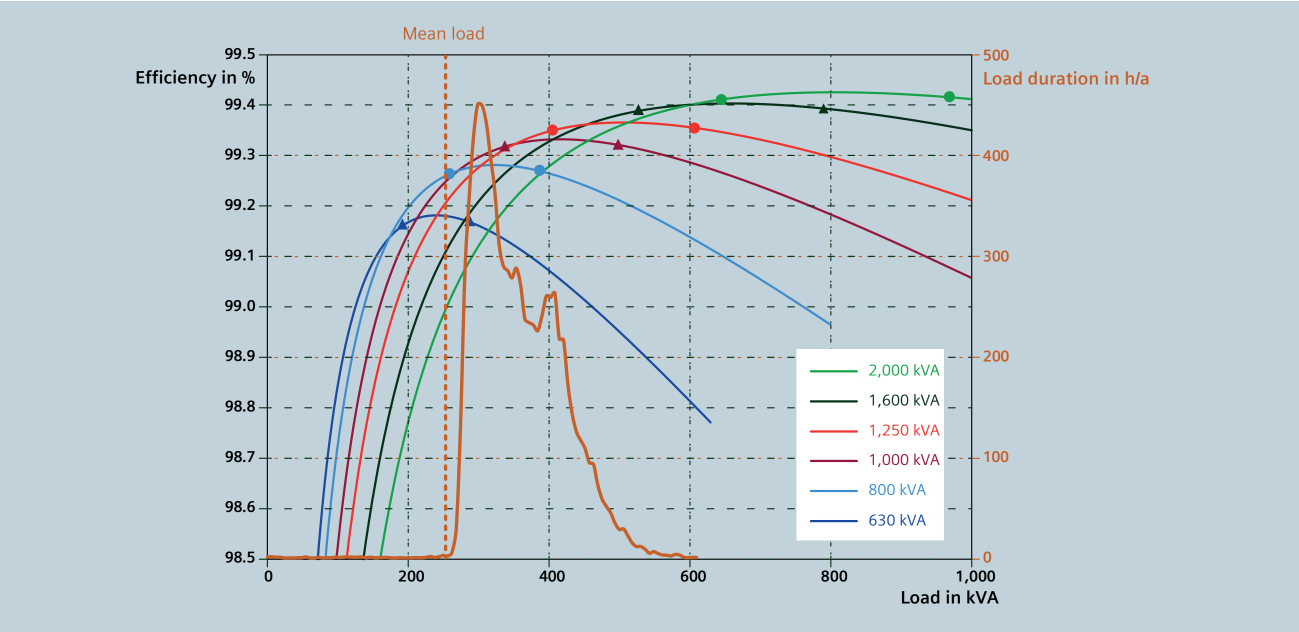
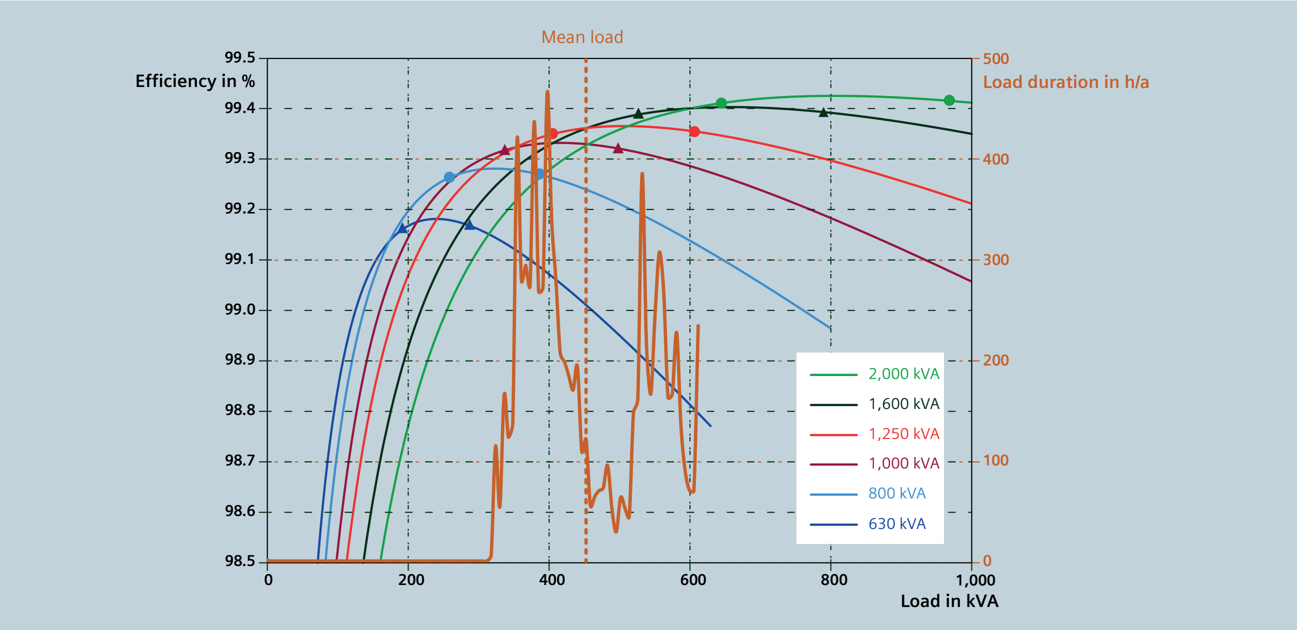


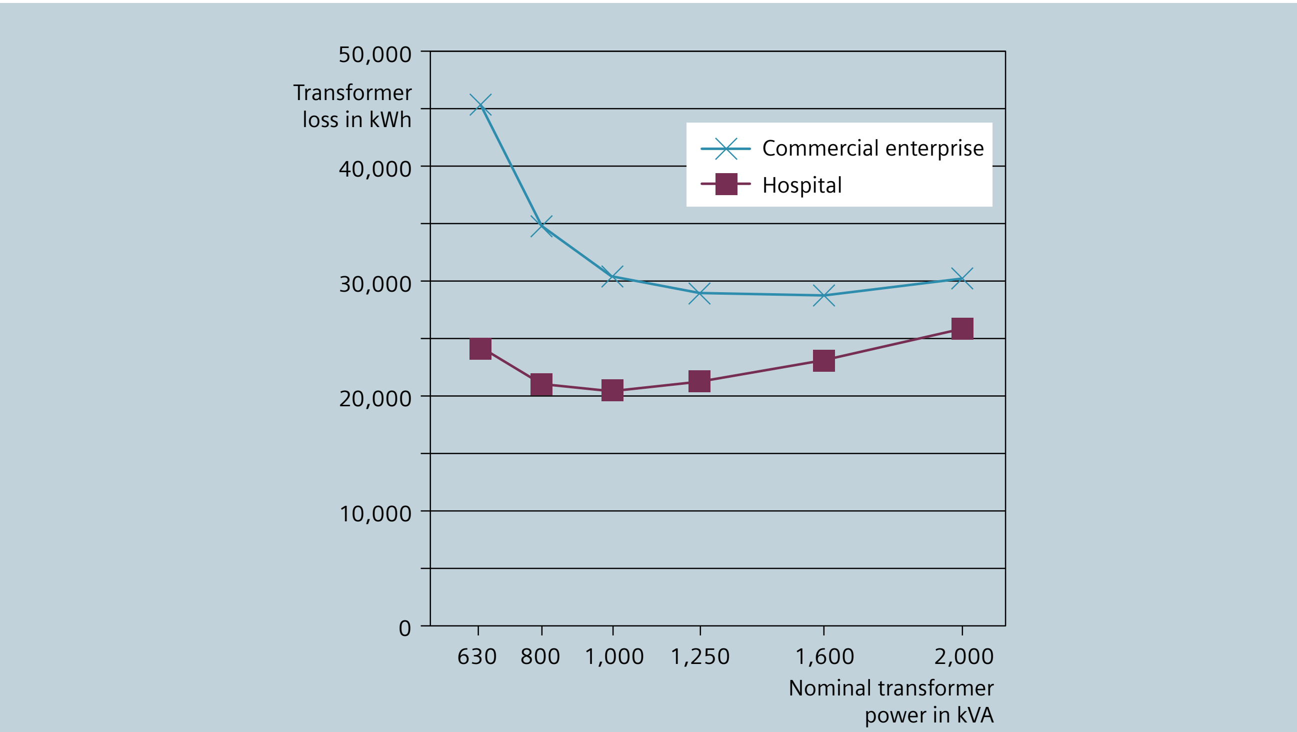
Fig. 5: Utilisation profile of a commercial enterprise and comparison of
efficiency curves of several transformers in compliance with IEC 60076-20 (VDE 0532-76-20)



For more precise interpretations, the transformer losses integrated over the corresponding utilisation profile are compared with those related to different transformer ratings as in Fig. 6. You can see that – as opposed to the simple comparison of efficiency curves with mean load situations in Fig. 4 and Fig. 5 – the transformers featuring a somewhat higher rating would have the lowest energy losses.

For the hospital, the loss minimum is with the 1,000-kVA transformer, for the commercial enterprise it is with the 1,600-kVA transformer. As demonstrated later in an example in chapter 7, this evaluation should be complemented by a profitability evaluation [2]. Such a calculation can be performed by the Siemens Consultant Support.

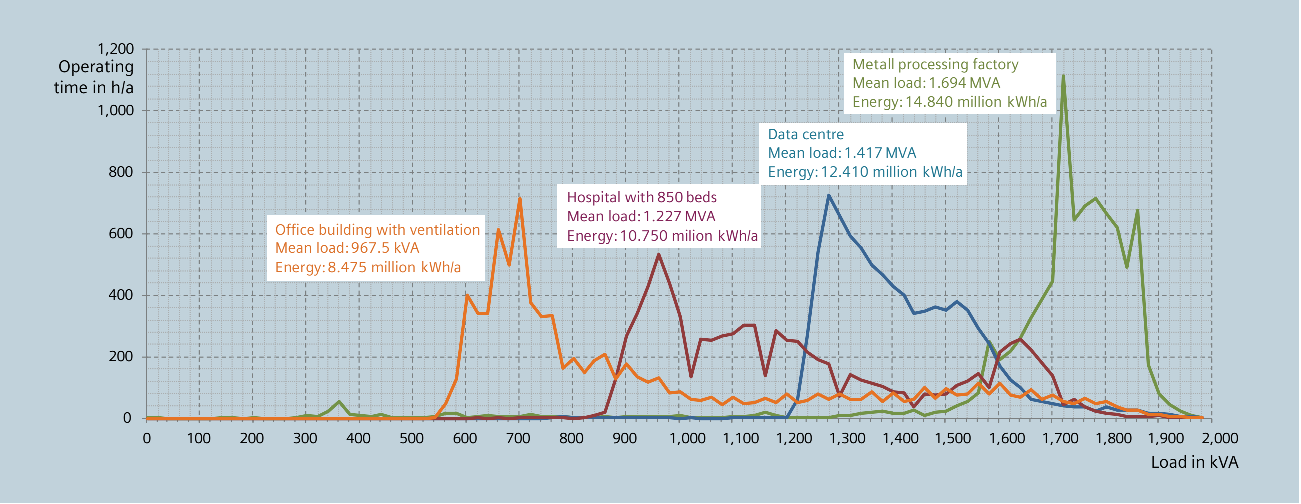
Fig. 6: Transformer losses for utilisation profiles and mean loading
(hospital as in Fig. 4 and commercial enterprise as in Fig. 5) dependent on transformer type and output



5. Parallel transformer operation

For reasons of supply reliability, several transformers are often connected in parallel and operated redundantly if necessary. Below, four different application cases with a peak output of 2,000 kVA and different utilisation profiles (Fig. 7) are considered. Annual energy losses are determined for different transformer configurations (different numbers and ratings of transformers). In all cases, the peak output can be supplied by (n-1) transformers, whereas the whole number of transformers (n) is being operated for the loss evaluation (n = 2, 3, 4 or 5). In the configuration with two 1,600-kVA transformers, the option of temporal transformer overloading by means of fan cooling is included in the considerations. Transformer downtimes or their load-dependent connecting into or disconnecting from supply are not taken into account in these loss calculations.

Fig. 7: Utilisation profiles and mean load for an office building, a hospital, a data centre, and a metal-processing factory with a peak power demand of 2,000 kVA



(n-1) transformers must be capable of supplying a peak output of 2,000 kVA, so that the following configurations for transformer ratings of 630 kVA and more will be considered:

- 630 kVA	n = 5
- 800 kVA	n = 4 and 5
- 1,000 kVA	n = 3, 4 and 5
- 1,250 kVA	n = 3, 4 and 5
- 1,600 kVA	n = 2*), 3, 4 and 5
- 2,000 kVA	n = 2, 3 and 4
- 2,500 kVA	n = 2, 3 and 4
- 3,150 kVA	n = 2, 3 and 4

*) Note: In transformer configurations featuring 2 x 1,600 kVA, ventilated transformers must be used, so that in (n-1) operation a performance increase by up to 25% can be attained for the individual transformer (in the performance range between 1,600 and 2,000 kVA).

Fan losses can be neglected compared to load losses with the load factors

$S_{Load} / S_r \geq 1$.

This results in 22 different loss values for the four different utilisation profiles:

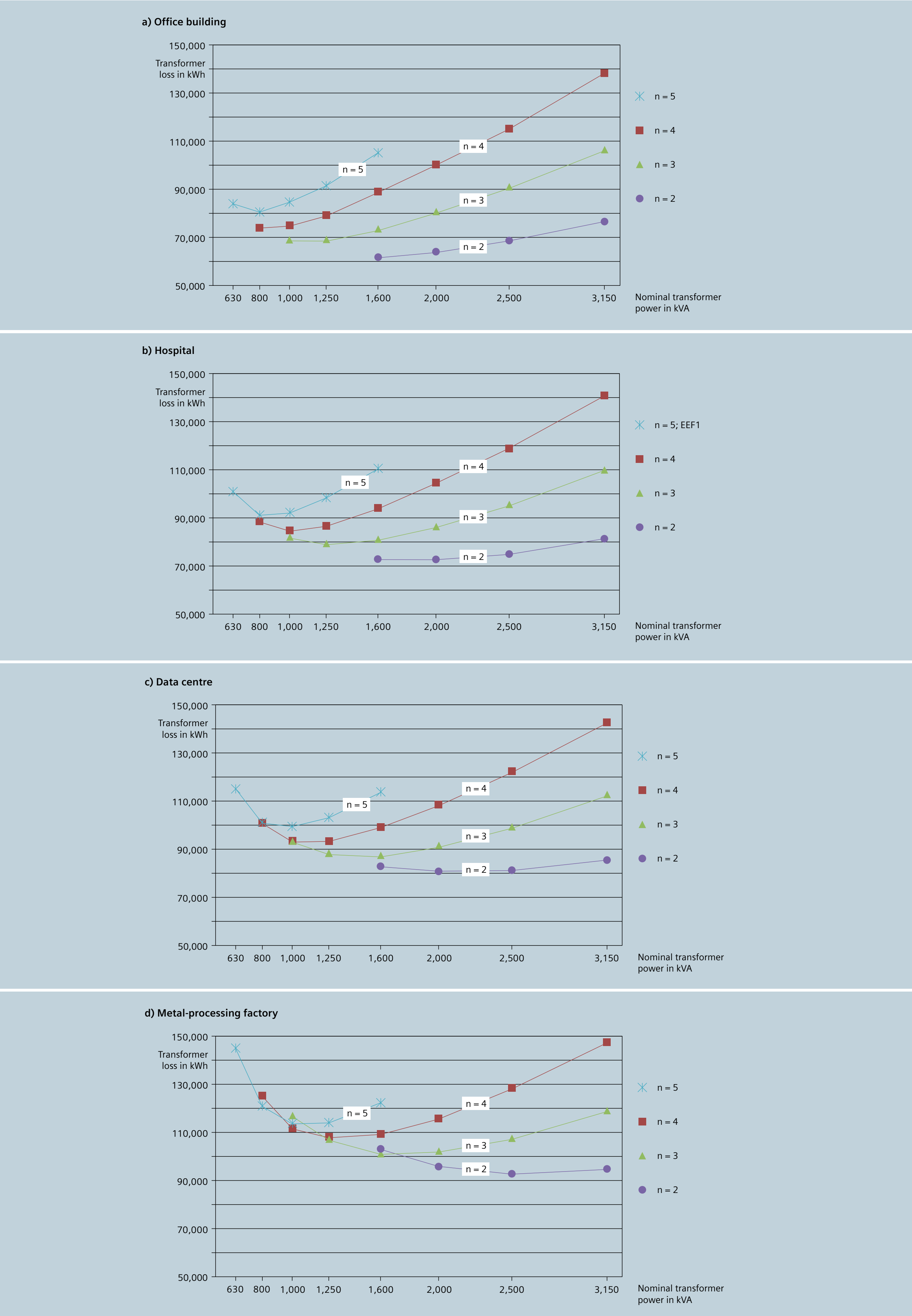
$$W_V = n \cdot [(P_0 \cdot T) + (\frac{P_k}{(n \cdot S_r)^2} \cdot \int_{t=0}^{T} S_{Last}(t)^2 \, dt)]$$

where

W_V	loss energy
n	number of transformers
T	time period considered
S_r	nominal apparent power of transformers
S_{Load} (t)	apparent power at a certain time t

Figure 8 on the next page presents the individual values translated in curves.

Fig. 8: Transformer losses in different applications and parallel configurations at 2,000 kVA peak for:
a) Air-conditioned office building
b) Hospital
c) Data centre
d) Metal-processing factory



The lowest energy losses are always seen in a configuration with n = 2. It is evident that the larger transformers tend to become more efficient under an increasing mean load, however at an overall higher level of energy loss. For example, for the office building, the configuration featuring two forced-ventilated 1,600-kVA transformers is energetically the most favourable one, whereas for the metal-processing factory, the two 2,500-kVA transformers show the lowest energy losses.

Note: This comparison of purely operational energy losses cannot replace any holistic analyses as to the so-called "ecological footprint", where the energy consumption and environmental influences of a product are identified over its entire life cycle from the manufacture to its disposal.

In order to assess the profitability of a certain transformer application, the investment-related costs and the demand charge differences incurred by power loss differences between transformers should at least be included in the analysis.

6. Cost analysis

For a total cost analysis of transformer use, several sub-amounts for investment and transformer operation are added up:

Total cost = (cost of depreciation and financing) plus (cost for no-load losses and load losses) plus (demand charge for the total power loss)

It is important that additional costs of investment for additional panels in medium- and low-voltage switchgear be also included in the calculation. Corresponding amounts for interest service and depreciation must also be taken into account. Besides operational factors such as the peak power demand, utilisation profile, distribution system topology and transformer properties, every cost analysis depends on numerous other factors such as the interest rate, electricity price, demand charge and depreciation period, so that an individual analysis must be performed for every project.

For illustration, three transformer configurations with relatively low power losses are compared. This example shall represent an air-conditioned office building as in Fig. 8a:

- 3 x 1,000-kVA transformer, GEAFOL ecodesign
- 2 x 2,000-kVA transformer, GEAFOL ecodesign
- 2 x 1,600-kVA transformer, GEAFOL ecodesign with additional ventilation

The low-voltage distribution system has not been structured and a cost analysis for different components in the distribution system is not made.

In Fig. 8a) losses for a transformer configuration featuring 3 x 1,000 kVA (approx. 64,800 kWh p.a.) are somewhat higher than for a configuration featuring 2 x 2,000 kVA (approx. 62,000 kWh p.a.). In turn, these losses are a little higher than the losses in a configuration featuring 2 x 1,600 kVA plus ventilation (approx. 59,400 kWh p.a.). If only the power consumption in ongoing operation is considered, the ventilated solution of 2 x 1,600 kVA is the most cost-effective one.

Concerning the demand charge, especially for transformer power losses, it is important to note that the values relating to a 2,000-kVA load during normal operation must be compared to the values for (n-1) operation. Power loss values in (n-1) operation are always higher for those transformer configurations under analysis than the ones during normal operation, and the single ventilated 1,600-kVA transformer will always have the highest power value at a 2,000-kVA load on account of the power loss.

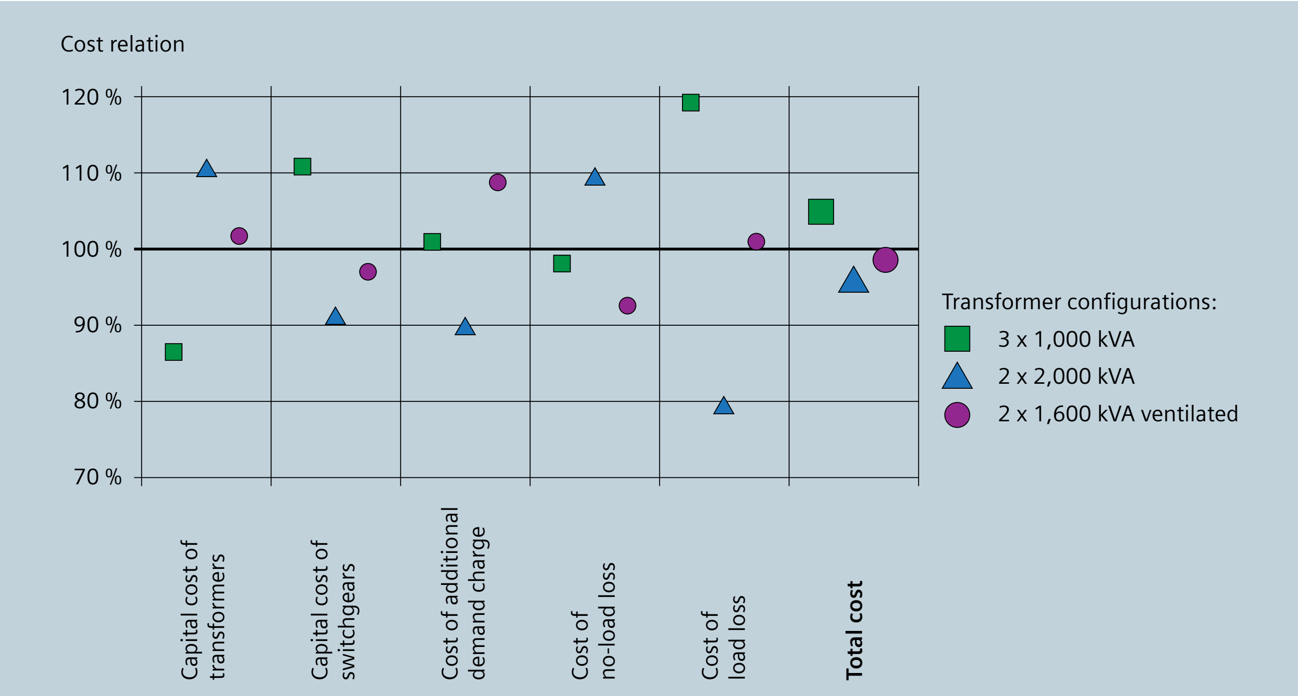
As to the investment cost for switchgear installations required in the different configurations, the additional panel for the third transformer B (3 x 1,000-kVA transformer configuration) plays an important part in the medium-voltage switchgear as well as in the low-voltage switchgear. SIMARIS planning tools may be used to facilitate switchgear and component dimensioning. In a simple calculation using SIMARIS design, the maximum short-circuit currents for the low-voltage distribution system rise from approx. 67 kA (3 x 1,000 kVA) to roughly 71 kA (2 x 1,600 kVA, ventilated) and up to approx. 86 kA (2 x 2,000 kVA). This means that the transformer configuration featuring 2 x 2,000 kVA possibly requires the use of more expensive protection devices with a better short-circuit current zone, i.e. a better performance category, to handle the short-circuit current in the distribution system.

The cost difference between the 2 x 2,000-kVA configuration and the ventilated 2 x 1,600-kVA configuration concerning the switchgear results from the different circuit breaker models installed in the low-voltage switchgear. The ventilated transformers have a higher maximum permissible output power (150 % x 1,600 kVA = 2,400 kVA; maximum current approx. 3,460 A) than the 2,000-kVA transformers (maximum current approx. 2,890 A), so that the circuit breakers to be installed must be chosen from a higher performance class (nominal current I_n). Owing to the lower secondary-side maximum short-circuit current, the outgoing feeder is somewhat cheaper for the ventilated configuration than for the 2 x 2.000-kVA configuration.

Fig. 9 illustrates the cost relations between the different configurations split into individual cost items and the total cost. Since the whole consideration is a fictitious example for a selected utilisation profile and fraught with many more assumptions, the diagram only shows relations but no monetary amounts.

A total cost analysis shows that in the given framework, the configuration featuring 2 x 2,000 kVA is slightly more cost-effective than the configuration featuring 2 x 1,600 kVA with ventilation and yet about 7% more cost-effective than the 3 x 1,000-kVA configuration. What is relevant here is the higher cost for the additional switchgear panels of the third transformer.

Fig. 9: Cost relations of the transformer configurations under analysis, referred to the mean values for individual cost factors and the total cost



7. Conclusion

Efficiency evaluations of transformers should always take into account their operating conditions. For the parallel operation of transformers, especially when an (n-1) redundancy is called for, the transformer rating matching the maximum power demand with a (2-1) redundancy proves to be the most cost-effective variant. However, the development of performance requirements should go into the selection and the planning of power reserves. Retrofitting has quite a significant effect on the cost calculation.

The use of ventilated transformers with a lower rating than the required peak output only seems to make economic sense with certain utilisation profiles. In any case, the cost situation should be roughly clarified for the whole operating period. For instance, a change of the required peak output to 2,200 kVA, instead of the 2,000 kVA analysed in the example, might yield a different result. In that case, the two ventilated 1,600-kVA transformers would cause a lower power loss and also lower total costs than two 2,500-kVA transformers. And in the 2,000-kVA variant, it would now be three transformers which would have to be procured plus the corresponding number of additional panels for the switchgear.

Bibliography:

[1] EU Regulation no. 548/2014 of the European Commission of 21 May 2014.

[2] Planning of Electric Power Distribution - Technical Principles, Siemens AG, 2015

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