To have a better understanding the impact of different loading on the transformer lifetime as well as the economy depreciation. We will first talk about the transformer losses, and then introduce the two concepts: Total owning cost (TOC) and lifetime loss, as well as the mathematics models.

1. Transformer Losses

Power transformer losses can be divided into two main components: no-load losses and load losses. These types of losses are common to all types of transformers, regardless of transformer application or power rating [1].

No-Load Losses

These losses occur in the transformer core whenever the transformer is energized (even when the secondary circuit is open). They are also called iron losses or core losses and are constant for 24/7. They are composed of:

- Hysteresis losses, caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. Hysteresis losses are usually responsible for more than a half of total no-load losses (50% to 80%).
- Eddy current losses, caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. Eddy current losses usually account for 20\% to 50\% of total no-load losses.

Load Losses

These losses are commonly called copper losses or short circuit losses. Load losses vary according to the transformer loading. They are composed of:

- Ohmic heat loss, sometimes referred to as copper loss, since this resistive component of load loss dominates. The magnitude of these losses increases with the square of the load current and is proportional to the resistance of the winding.
- Conductor eddy current losses (neglectable). Eddy currents, due to magnetic fields caused by alternating current, also occur in the windings.

Extra losses are not considered, for example, the loss caused by harmonics or losses which may apply particularly to larger transformers – cooling or auxiliary losses, caused by the use of cooling equipment like fans and pumps.

2. Total Owning Cost

The common practice used by the electric utilities for determining the cost-effectiveness of distribution transformers is based on the total owning cost (TOC) method, where TOC is equal to the sum of transformer-purchasing price plus the cost of transformer losses throughout the transformer lifetime [2].

A transformer bid typically specifies the bid price, no-load losses in watts, and load-losses in watts. These loss values should be provided by the manufacturer. A basic method of transformer evaluation is to assign a cost per watt for both the no-load and load-losses. The cost per watt for no-load losses is the transformer design *A* value, and the cost per watt for load-losses is the transformer design *B* value. The *A* and *B* values help to determine the total ownership cost of the losses on any given transformer with a load-loss and no-load loss value.

The *A* and *B* values include the cost of no-load and load losses in the TOC formula:

$$TOC = BP + A \times NLL + B \times LL$$

where *BP* is the fixed biding price, *NLL* is the no-load losses, *LL* is the load loss in watts at the transformer's rated load.

3. Transformer Lifetime Estimation

The life of a power transformer mainly depends on the condition of the paper-oil insulation system [3]. Aging or deterioration of insulation is a time function of temperature, moisture content, and oxygen content. With modern oil preservation systems, the moisture and oxygen contributions to insulation deterioration can be minimized, leaving the temperature as the dominate parameter [4].

Since, in most apparatus, the temperature distribution is not uniform, the part that is operating at the highest temperature will ordinarily undergo the greatest deterioration. Therefore, in aging studies it is usual to consider the aging effects produced by the highest (hottest-spot) temperature T_{HS}.

For a given temperature of the transformer insulation, the transformer insulation life is the total time between the initial state for which the insulation is considered new and the final state for which dielectric stress, short circuit stress, or mechanical movement, which could occur in normal service, and could cause an electrical failure. Experimental evidence indicates that the relation of insulation deterioration to time and temperature follows an adaptation of the Arrhenius reaction rate theory that has the following form:

$$P.U.\ \ Life = 9.8 \times 10^{-18} \exp\left(\frac{15000}{T_{HS} + 273}\right)$$

The IEEE guide recommends that users select the assumptions for lifetime estimation. In the IEEE C57.91 guide, 20.5 years is considered as the normal lifetime of a power transformer [4]. A lifetime with the constant hottest temperature relationship is shown in Fig. 1. Note if the hottest-spot temperature T_{HS} is constantly 110˚C, the per-unit life is 1, and the lifetime is 20.5 years when T_{HS} is constantly 110 ˚C.

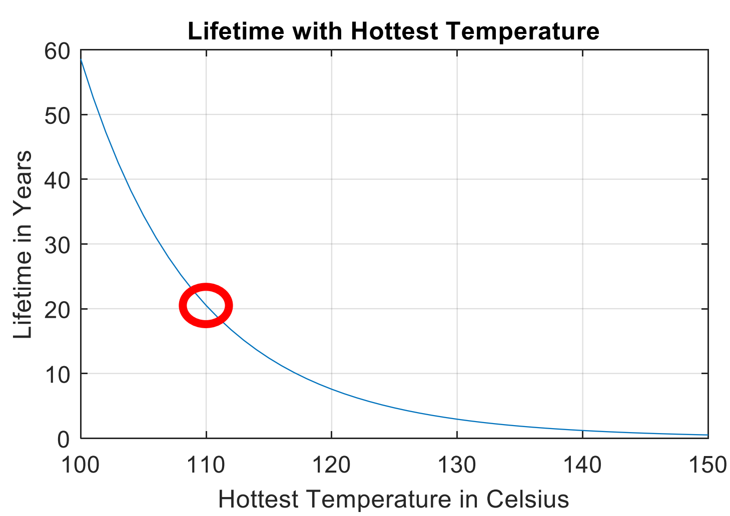


Fig. 1 Relationship between transformer lifetime with the constant hottest temperature

The hottest-spot temperature T_{HS} consists of three components given by the following equation:

$$T_{HS} = T_{amb} + \Delta T_{TO} + \Delta T_{W}$$

where T_{amb} is the ambient temperature, ΔT_{TO} is the top oil temperature rise over the ambient, and ΔT_{W} is the winding hottest spot temperature rise over the oil.

The steady-state calculations for ΔT_{TO} and ΔT_{W} are:

$$\Delta T_{TO,SS} = \Delta T_{TO}^{ref} \left[\frac{K_U^2 R + 1}{R + 1} \right]^n$$

$$\Delta T_{W,SS} = \Delta T_{W}^{ref} K_U^{2m}$$

where ΔT_{TO}^{ref} and ΔT_{W}^{ref} are the values under nominal loading level, *n* and *m* are the thermal exponent coefficients, R is the ratio of load loss (at nominal loading level) to no-load loss, and K_U is the loading level:

$$K_U = I_{load} / I_{rated}$$

For any time step *t*, the dynamic equations for ΔT_{TO} and ΔT_{W} are:

$$\Delta T_{TO} = \left(\Delta T_{TO,SS} - \Delta T_{TO,i} \right)\left(1 - e^{-t/\tau_{TO}} \right) + \Delta T_{TO,i}$$

$$\Delta T_{W} = \left(\Delta T_{W,SS} - \Delta T_{W,i} \right)\left(1 - e^{-t/\tau_{W}} \right) + \Delta T_{W,i}$$

where $\Delta T_{TO,i}$ and $\Delta T_{W,i}$ are the initial values, τ_{TO} and τ_{W} are the thermal time constants.

In summary, with the information of loading level and ambient temperature, we can calculate the hottest-spot temperature in the transformer.

An aging acceleration factor F_{AA} is calculated for a given load and temperature or for a varying load and temperature profile over a period of time. The F_{AA} stands for the rate at which transformer insulation aging is accelerated compared with the aging rate at a reference hottest-spot temperature. The equation for F_{AA} is as follows:

$$F_{AA} = \exp\left(\frac{15000}{110 + 273} - \frac{15000}{T_{HS} + 273} \right)$$

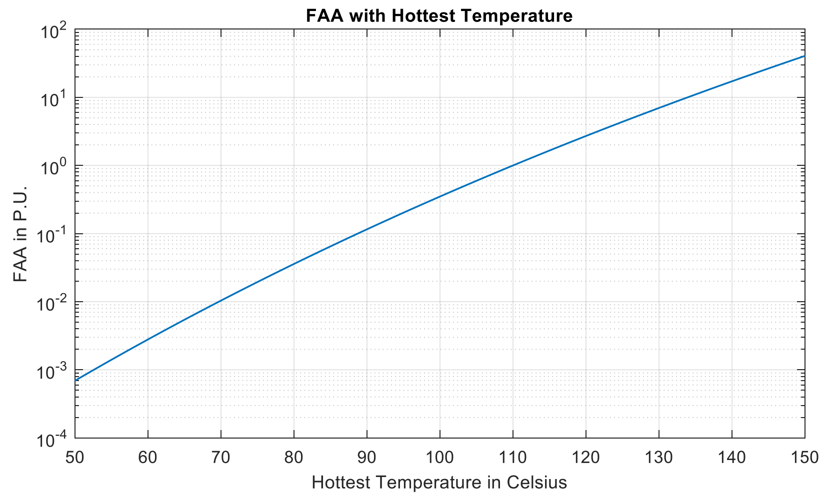


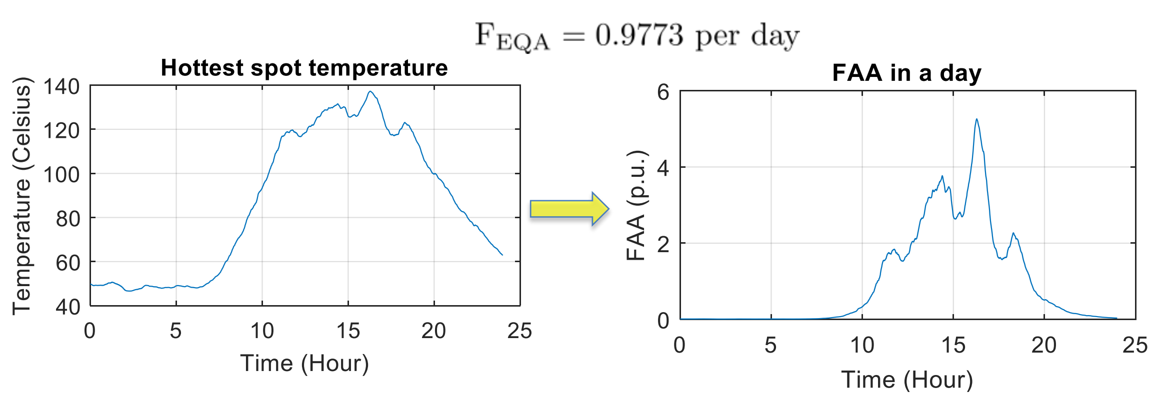
Fig.2 Relationship between aging acceleration factor and the hottest-spot temperature

The relationship between aging acceleration factor F_{AA} and the hottest-spot temperature T_{HS} is shown in Fig. 2. For hottest-spot temperatures in excess of the reference hottest-spot temperature, the aging acceleration factor is greater than 1.0. For hottest-spot temperatures lower than the reference hottest-spot temperature, the aging acceleration factor is less than 1.0.

The aging acceleration factor F_{AA} can be used to calculate the equivalent aging factor F_{EQA} as

$$F_{EQA} = \frac{\sum_{i=1}^{N} F_{AA,i} \Delta t_i}{\sum_{i=1}^{N} \Delta t_i}$$

Equivalent aging factor F_{EQA} denotes the rate at which transformer insulation aging is accelerated or decelerated when the hottest-spot temperature is different from 110˚C over a period of time. Fig. 3 shows an example of calculating F_{AA} and F_{EQA}. Fig. 3(a) shows the hottest spot temperature during a day and Fig. 3(b) is the corresponding aging acceleration factor during the day. With the above equation we can know the equivalent aging factor is 0.9773, which means the transformer lifetime loss during this full day is equivalent to 0.9773 days if it is constantly working with hottest-spot temperature is 110˚C.



(a) (b)

Fig. 3 An example of calculating F_{AA} and F_{EQA} from hottest spot temperature

Based on the equivalent aging factor F_{EQA} during a period of time ΔT, we can project the lifetime of transformer if the operating condition does not change,

$$L = \frac{L_{nominal}}{F_{EQA}}$$

Finally we can calculate the transformer operating cost over the period of time, as shown in Fig. 4.

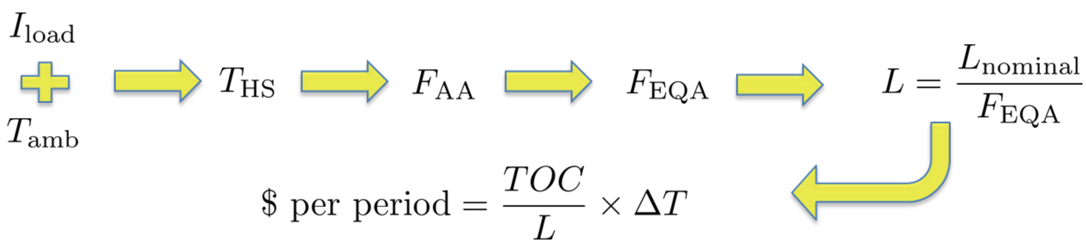


Fig. 4 Flowchart of transformer operating cost over the period of time

An example of the relationship between loading level and the cost per five minutes is shown in Fig. 5, where the TOC of the transformer is \$100K and the ambient temperature is 30 ˚C.

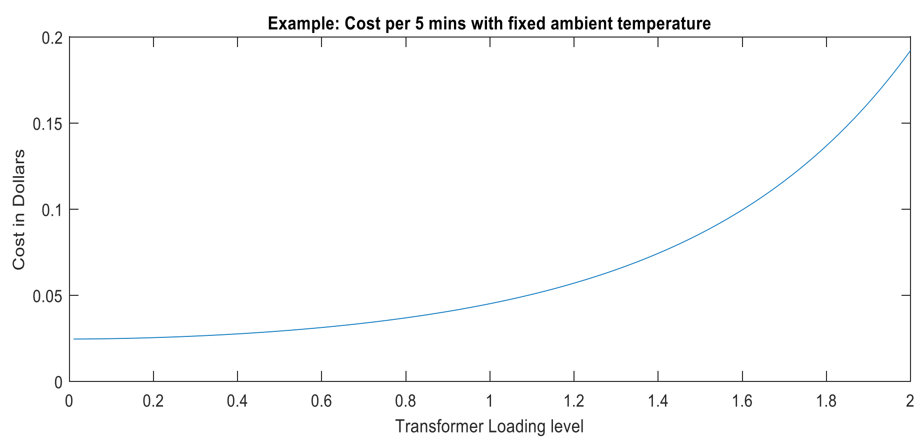


Fig. 5 An example of calculating transformer operating cost over five minutes

Reference

[1] Harlow, James H. *Electric power transformer engineering*. CRC press, 2012.

[2] Kennedy, Barry W. *Energy efficient transformers*. McGraw-Hill Professional Publishing, 1998.

[3] Oommen, T. V., and Thomas A. Prevost. "Cellulose insulation in oil-filled power transformers: part II maintaining insulation integrity and life." *IEEE Electrical Insulation Magazine,* 22.2 (2006): 5-14.

[4] Board, I. "IEEE guide for loading mineral-oil immersed transformers." *IEEE Standard C* 57 (1995): 1-112.

Second method of calculating the transformer operating cost

The second method is more about real-time costs, the cost during a period of time ΔT is:

$$Cost = Cost(BP) + Cost(energy\ loss)$$

Where the cost of purchasing price is

$$Cost(BP) = \frac{BP}{L_{nominal}} \times \Delta T \times F_{EQA}$$

The cost of energy loss is

$$Cost(energy\ loss) = Price \times \left(NLL + LL \times K_U^2 \right) \times \Delta T$$