Transformer overloading – a necessary evil, but at what cost

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I INTRODUCTION

Transformers are designed for a certain maximum load current (power) level. For higher currents, the losses will be higher, and the temperature of the transformer will increase. As the temperature increases, hot spots in the transformer windings can occur that degrade the paper insulation, increasing the potential for internal faults. Operating at high temperatures will evaporate water from the insulation paper into the oil. This will lead to overall degradation in the quality of the oil, reducing its cooling and insulation properties.

In certain operational situations in the power system it can be required to overload transformers for a limited time. The thermal overload protection function (49 function) is designed to permit such temporary overloading of transformers. However, this function has typically not been used in transformer protection schemes.

II PRC-023

PRC-023 states that protective relay settings shall not limit transmission loadability, and shall not interfere with system operators' ability to take remedial action to protect system reliability.

For transformer overload protection relays, PRC-023 states that these relays must be set according to one of the following:

- Set the relays to allow the transformer to be operated at an overload level of at least 150% of the maximum applicable nameplate rating, or 115% of the highest operator established emergency transformer rating, whichever is greater, for at least 15 minutes, to provide time for the operator to take controlled action to relieve the overload.
- Install supervision for the relays using either a top oil or simulated winding hot spot temperature element set no less than 100°C for the top oil temperature, or no less than 140°C for the winding hot spot temperature.

Source: PRC-023-5, §B R1-11

III TRANSFORMER THERMAL OVERLOAD PROTECTION (49)

The 49 function is a thermal overload protection function that continuously estimates the internal heat content (temperature) of the transformer using a thermal model based on current measurement. The heat content depends on the heat that is produced by the losses inside the transformer (no-load and load losses). Predominantly, the load losses are proportional to I^2.

A loaded transformer with constant load current $I_{initial}$ has initial heat content $\theta_{initial}$ (corresponding to initial temperature $T_{initial}$). If the load current undergoes a step change to I_{final} ($I_{final} > I_{initial}$), the heat content (and temperature) of the transformer will increase.

Figure 1: Step change increase in the transformer current

The step change in current occurs at time t = 0. The equation for θ_t, the heat content at time t, is:

$$\Theta_t = \Theta_{initial} + ((\Theta_{final} - \Theta_{initial}) * (1 - e^{-\frac{t}{\tau}}))$$

Equation 1

t =	Θ_t =
0	$\Theta_{initial}$
$1 * \tau$	$\Theta_{initial} + 0.632*(\Theta_{final} - \Theta_{initial})$
$2 * \tau$	$\Theta_{initial} + 0.865*(\Theta_{final} - \Theta_{initial})$
$3 * \tau$	$\Theta_{initial} + 0.950*(\Theta_{final} - \Theta_{initial})$
$4 * \tau$	$\Theta_{initial} + 0.982*(\Theta_{final} - \Theta_{initial})$
$5 * \tau$	$\Theta_{initial} + 0.993*(\Theta_{final} - \Theta_{initial})$
$6 * \tau$	$\Theta_{initial} + 0.998*(\Theta_{final} - \Theta_{initial})$

Table 1: Θ_t at specific times t following the step change in current (Figure 1)

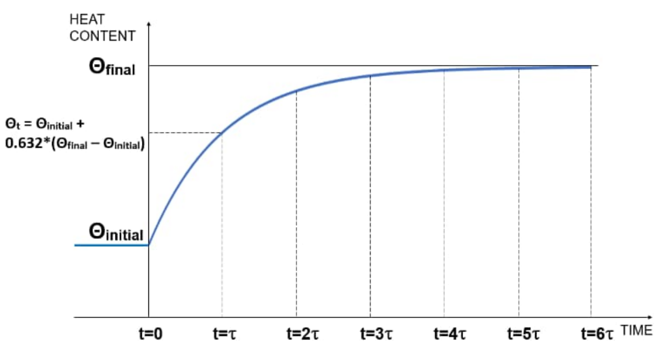


Figure 2: Rise in heat content Θ resulting from the step change in current (Figure 1)

It is necessary to set an operate threshold for the thermal overload function. This is set as a current threshold $I_{operate}$. The heat content operate threshold $\Theta_{operate}$ is derived internal to the thermal overload function from the set $I_{operate}$ threshold (the heat content Θ is proportional to I^2). If $I_{operate}$ were to flow continuously, the heat content would (eventually) reach $\Theta_{operate}$. For current flow less than $I_{operate}$, $\Theta_{operate}$ would never be reached, and for current flow greater than $I_{operate}$, $\Theta_{operate}$ would be reached sooner.

Based on the initial current (< $I_{operate}$) and the final current (> $I_{operate}$) due to a step change, the time it will take the heat content to reach $\Theta_{operate}$ is given by the following equations:

$$t_{operate} = \tau * \ln\left(\frac{\Theta_{final} - \Theta_{initial}}{\Theta_{final} - \Theta_{operate}}\right)$$

$$= \tau * \ln\left(\frac{I_{final}^2 - I_{initial}^2}{I_{final}^2 - I_{operate}^2}\right)$$

Equation 2

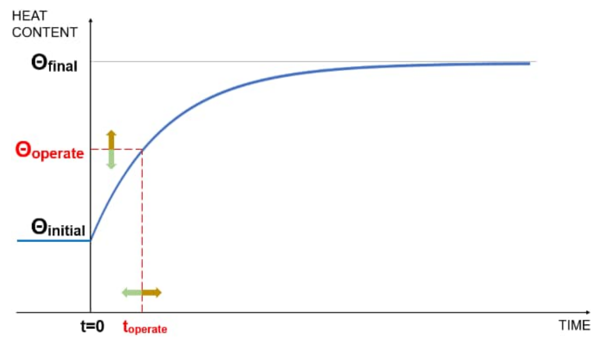


Figure3: $t_{operate}$ for set $\Theta_{operate}$ for the step change in current (Figure 1)

From Figure 3 is can be clearly seen that:

- for a higher set $\Theta_{operate}$, $t_{operate}$ will increase
- for a lower set $\Theta_{operate}$, $t_{operate}$ will decrease

The thermal protection algorithm continuously calculates a new value for the heat content Θ after every time interval Δt (e.g. Δt = 100ms). The new value for Θ (Θ_n) calculated for the n^{th} time step is equal to the calculated value one step back (Θ_{n-1}) plus the change in Θ in the Δt time interval between steps n-1 and n. Fluctuations / changes in current occur continuously. Therefore, Θ_{final} must be determined for each calculation step. Θ_{final_n} for the n^{th} step calculation is based on the value of the current at the time of the n^{th} step calculation. Θ_{final_n} is the final value for the heat content that would be reached were this current to continue unchanged until this final value for the heat content were reached.

For $\Theta_{final\_n} > \Theta_n$ (heating) the equation for the change in Θ ($\Delta\Theta_n$) in the time interval Δt between calculation steps n-1 and n is:

$$\Delta\Theta_n = ((\Theta_{final\_n} - \Theta_{n-1}) * (1 - e^{-\frac{\Delta t}{\tau}}))$$

Equation 3

from which Θ_n, the heat content calculated for the n^{th} step, is:

$$\Theta_n = \Theta_{n-1} + \Delta\Theta_n$$

Equation 4

IV LOSS OF LIFE

The life of a mechanically sound transformer depends mainly on the life of its insulation paper. Deterioration of the insulation paper is mostly affected by temperature, as the impact from other factors can be controlled and kept to a minimum. As the winding temperature distribution inside a transformer is not uniform, the insulation paper at the winding hot spot will likely deteriorate the most. Therefore, a mechanically sound transformer's overloading capability and its life expectancy are determined by the magnitude and duration of the hottest spot temperature of the windings.

Equations derived in the IEEE standard C57.91-2011 or the IEC standard 60076-7, Edition 2.0, 2018-01 can be used to calculate:

- the top oil temperature
- the winding hot spot temperature
- the aging rate of the winding insulation (based on the hot spot temperature)
- loss of life (based on the aging rate)
- the accumulated loss of life

The aging rate V for non-upgraded paper insulation is given by the equation:

$$V = 2^{(\Theta_{hmax} - 98)/6} \qquad \text{Equation 5}$$

and for upgraded paper insulation by the equation:

$$V = e^{\left[\frac{15000}{110+273} - \frac{15000}{\Theta_{hmax}+273}\right]} \qquad \text{Equation 6}$$

Θ_h = the winding hot spot temperature

For interest, Table 2 shows the aging rate for both non-upgraded as well as upgraded paper insulation for increasing values of Θ_h.

The typical expected life of a transformer is 7300 days (20 years) with a continuous aging rate of 1. The expected life is lengthened, or shortened, for a lifetime average aging rate of, respectively, less than 1 or greater than 1.

Figure 4 illustrates this from the perspective of remaining life (top) and loss of life (bottom).

θ_h °C	Non-upgraded paper insulation V	Upgraded paper insulation V
80	0,125	0,036
86	0,25	0,073
92	0,5	0,145
98	**1,0**	0,282
104	2,0	0,536
110	4,0	**1,0**
116	8,0	1,83
122	16,0	3,29
128	32,0	5,8
134	64,0	10,1
140	128,0	17,2

The indicated relative ageing rate V = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper.

Source: IEC 60076-7 Edition 2.0

Table 2: Aging rate dependence on hot spot temperature

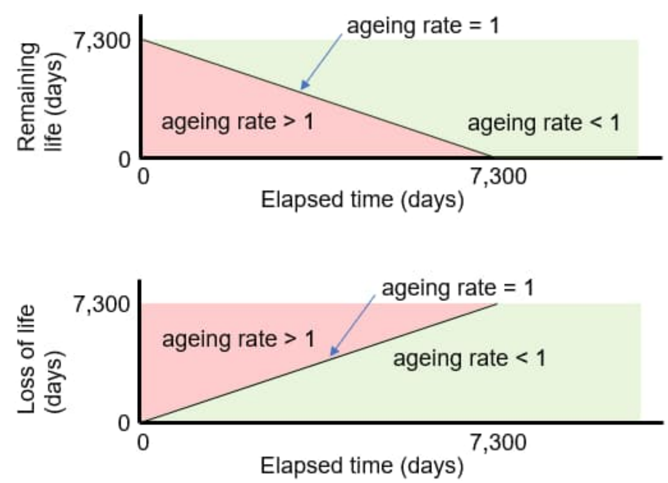


Figure 4: Remaining life (top) and loss of life (bottom) for aging rate > 1, = 1 and < 1

The loss of life algorithm continuously calculates a new value for the accumulated loss of life L after every time interval Δt (e.g. Δt = 100ms). The new value for L (L_n) calculated for the n^{th} time step is equal to the calculated value one step back (L_{n-1}) plus the change in L in the Δt time interval between steps n-1 and n.

$$\Delta L_n = V_n * \Delta t \qquad \text{Equation 7}$$

where:
V_n is the aging rate at the time of the nth time step, and Δt is the time interval having aging rate V_n.

L_n, the accumulated loss of life calculated at the nth step, is:

$$L_n = L_{n-1} + \Delta L_n \qquad \text{Equation 8}$$

V TRANSFORMER OVERLOADING

In a stressed situation the need may arise to overload a transformer beyond its nameplate rating. Under such circumstances it may be critical that the transformer stays in service for as long as possible. It becomes a very hard decision for the operator to take the transformer out of service. However, if implemented, the thermal overload protection will, at some point, operate and remove the transformer from service in accordance with its applied settings. Any operator reluctance to remove the transformer from service is now overridden. Therefore, any operator intervention to remedy the overload situation must be taken within the time to trip of the thermal overload protection function.

For this reason, there is an apparent reluctance for utilities to apply thermal overload protection. In the words of two US utilities:

- "We do not implement thermal overload protection (by electrical means or otherwise) on transmission or area station transformers. Our general philosophy is that the operators are responsible for operating the system and have the freedom to deal with overloads and transformer heating as they see fit, in accordance with procedures. We would rather be given the chance to address any overloads than have the transformer automatically trip-out and make the situation worse"
- "We do not trip on 49T transformer thermal overload in our typical designs today. We just annunciate & alarm. We have administrative controls in place for monitoring overloads via our operators & SCADA"

Today's power grid is evolving to a distributed source / load architecture as distributed energy resources, e.g. inverter based resources, replace traditional centralized generation. The need to maintain islanded systems is rising, yet operators are not equipped to handle multi-islanded systems. These evolving complexities to grid operations and the ever extending lead times for power transformers should be considered. The following analysis makes the case for implementing transformer thermal overload protection (49 function) and loss of life monitoring.

VI LIFE LOST

The details of the transformer used as example in this paper are as follows:

150	MVA
161	kV, rated voltage HV-side
537.9	A, rated current HV-side
5	Number of taps on HV-winding 169.05 – 161 – 152.95kV Rated voltage tap: 3 High voltage tap: 1 Low voltage tap: 5
ONAF	Type of cooling
Upgraded paper	Type of insulation
120	minutes, oil time constant τ_o
4.8	minutes, winding time constant τ_w
9.9	Load to no load loss ratio at rated voltage tap
9.7	Load to no load loss ratio at high voltage tap
10.4	Load to no load loss ratio at low voltage tap
32.9	°C, steady state top oil temperature rise above ambient at rated load ($\Delta\Theta_{or}$)
32.5	°C, hot spot temperature rise above steady state top oil temperature at rated load ($\Delta\Theta_{hr}$)

Table 3: Transformer parameters

In this paper all calculations (top oil temperature, hot spot temperature and loss of life) are based on the equations given in IEC standard 60076-7, Edition 2.0, 2018-01.

The initial analysis to follow is based on a fixed ambient temperature (30°C), a fixed pre-overload level (1pu), a fixed overload level (1.5pu) and a fixed tap position (tap 3, the rated voltage tap).

A steady state current of 1pu flowing at an ambient temperature of 30°C gives rise to a hot spot temperature of 95°C, and this results in a steady aging rate V of 0.212. An aging rate of 0.212 means that for every minute the transformer is in service, it will age 0.212 minutes (i.e. it will lose 0.212 minutes of its expected life).

To get an aging rate of 1, a steady flow of 1.132pu current is required at an ambient temperature of 30°C. This gives rise to a hot spot temperature of 110°C, and for upgraded paper insulation this results in an aging rate of 1. An aging rate of 1 means that for every minute the transformer is in service, it will age 1 minute (i.e. it will lose 1 minute of its expected life).

The calculation method used to analyze the overload resulting from a step change from 1pu steady state current to 1.5pu steady state current is as follows:

- Calculate the steady state top oil temperature and hot spot temperature before the overload (i.e. before the step change in current). The pre-overload accumulated loss of life is taken as zero, because the intent with these calculations is to calculate the loss of life resulting from the level and duration of the overload.
- From the instant of the step change, calculate a new value for top oil temperature and hot spot temperature after every time interval Δt (mostly Δt = 1 minute was used, but also Δt = 100ms was used where more resolution was required). Calculate the accumulated loss of life after every time interval Δt starting from t_0 at the step change.

For a step change from a constant pre-overload current of $I_{initial}$ = 1pu to a constant overload current I_{final} = 1.5pu, operation of the thermal overload protection for an $I_{operate}$ setting = 1.1pu would be as follows:

$t_{operate}$ = 22 minutes.
This satisfies the requirements of PRC-023.

The life lost by the transformer during the 22 minute duration of the 1.5pu overload (from the step change until the trip) = 103 minutes.

Figure 5 illustrates the impact on $t_{operate}$ by increasing the $I_{operate}$ setting.

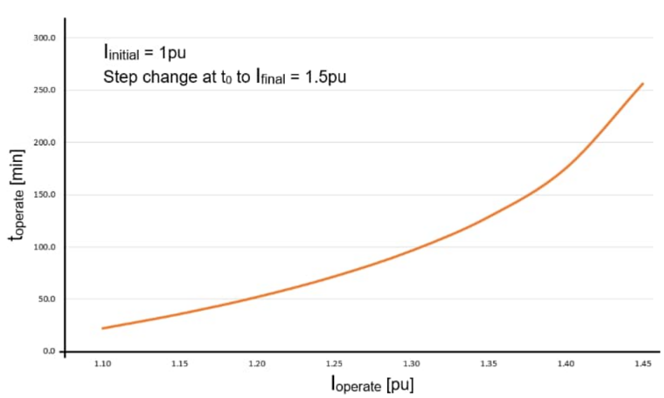


Figure 5: $t_{operate}$ for increasing $I_{operate}$

$t_{operate}$ increases from 22 minutes for $I_{operate}$ = 1.1pu to 256 minutes for $I_{operate}$ = 1.45pu.

Figure 6 illustrates the impact on the life lost by the transformer for the 1.5pu overload (from the step change until the trip) when increasing the $I_{operate}$ setting.

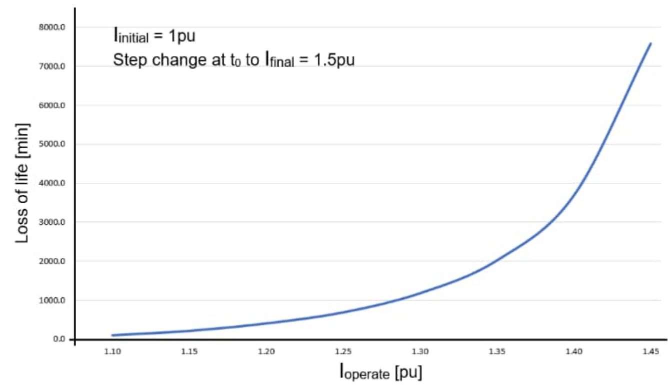


Figure 6: Life lost for increasing $I_{operate}$

The life lost by the transformer increases from 103 minutes for $I_{operate}$ = 1.1pu ($t_{operate}$ = 22 minutes) to 7578 minutes for $I_{operate}$ = 1.45pu ($t_{operate}$ = 256 minutes).

Table 4 and Figure 7 illustrate the direct relationship between the duration of the 1.5pu overload and the transformer's life lost.

Steady state current before overload			1.0 x rated current
Steady state overload current			1.5 x rated current
Duration of overload [min]	Loss of life [min]	Duration of overload [min]	Loss of life [min]
20	89	170	3483
30	169	180	3888
40	266	190	4313
50	381	200	4759
60	516	210	5223
70	672	220	5705
80	849	230	6205
90	1049	240	6721
100	1272	250	7252
110	1518	260	7798
120	1788	270	8358
130	2081	280	8931
140	2397	290	9516
150	2737	300	10112
160	3099		

Table 4: Resulting loss of life for a given overload duration

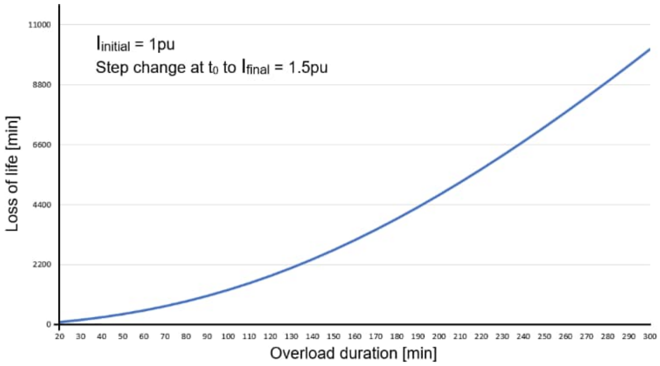


Figure 7: Resulting loss of life for a given overload duration

Based on achieving a desired time to operate (= overload duration) of thermal overload protection, an $I_{operate}$ setting can be chosen to achieve this. The larger the $I_{operate}$ setting the longer the transformer will remain in service, giving the operator more time to take action to remedy the situation.

Take, as example, that an $I_{operate}$ setting was chosen such that the time to operate for a 1.5pu overload would be 180 minutes (3 hours). The life lost by the transformer during the 1.5pu overload would be 3888 minutes. 3888 minutes seems a lot of life lost, but based on an expected life of 20 years, this represents just 0.037% of that expected life. However, it remains true that the transformer has lost 3888 minutes of life. Averaged over the 180 minutes, for every minute the transformer was in service with the 1.5pu overload it will have aged nearly 22 minutes. The actual aging rate at the 180 minute mark is 41, which means that at the 180 minute mark the transformer will age 41 minutes for 1 minute in service.

A transformer's life lost increases significantly the longer it's kept in service. If the transformer were to be kept in service for 240 minutes (4 hours), the life lost by the transformer would be 6721 minutes. Averaged over the 240 minutes, for every minute the transformer was in service with the 1.5pu overload it will have aged 28 minutes. The actual aging rate at the 240 minute mark is 52, which means that at the 240 minute mark the transformer will age 52 minutes for 1 minute in service.

Of course the opposite is true if the transformer is kept in service for a shorter time. If the transformer were to be kept in service for 120 minutes (2 hours), the life lost by the transformer would be 1788 minutes. Averaged over the 120 minutes, for every minute the transformer was in service with the 1.5pu overload it will have aged nearly 15 minutes. The actual aging rate at the 120 minute mark is 28, which means that at the 120 minute mark the transformer will age 28 minutes for 1 minute in service.

Figure 8 illustrates the change in the aging rate V over time for the 1.5pu overload.

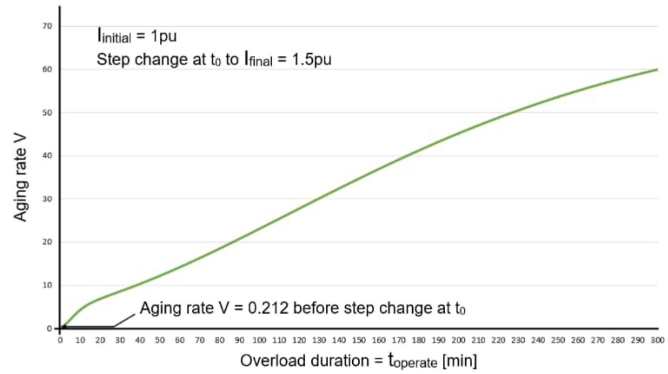


Figure 8: Aging rate V over time

As already stated, a steady current of 1pu flowing at an ambient temperature of 30°C results in a steady aging rate V of 0.212. For interest, if the 1.5pu overload were to persist indefinitely, a new steady aging rate would eventually be attained, but instead of 0.212 as for a steady current of 1pu, it would now be nearly 75. This is illustrated in Figure 9.

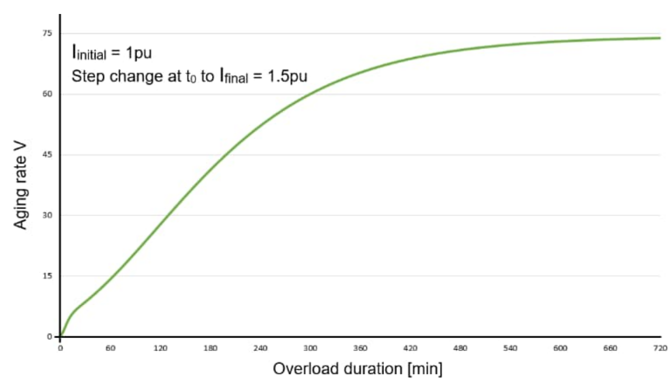


Figure 9: Aging rate V over time for persistent 1.5pu overload

As stated earlier (Equation 6), the aging rate is a function of the hot spot temperature Θ_h. The profile of the aging rate over time (Figures 8 & 9) directly follows its relationship to the hot spot temperature.

The profile of the hot spot temperature over time is illustrated in Figure 10. Before the step change in current, a steady state current of 1pu flowing at an ambient temperature of 30°C gives rise to a hot spot temperature of 95°C.

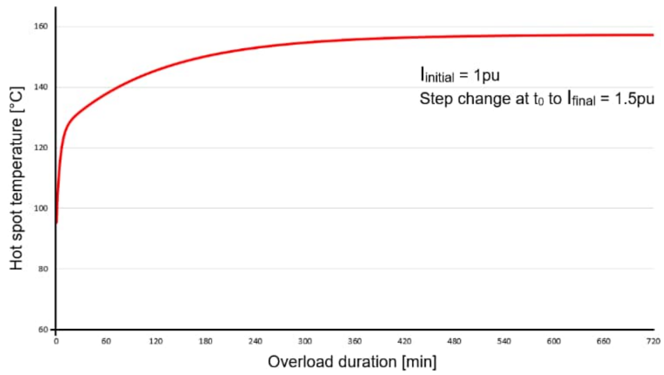


Figure 10: Hot spot temperature over time for a persistent 1.5pu overload

An overloaded transformer can have the overload removed in one of two ways:

- the overload is removed by some intervening action, thereby allowing the transformer to be kept in service
- the overload is removed by taking the transformer out of service, either through operator action or a protection trip

Figure 11 illustrates the difference in the aging rate for:

(a) the 1.5pu overload steps down to 1pu after an overload duration of 180 minutes – the aging rate will eventually return to the steady rate of 0.212 for 1pu current flow

(b) the 1.5pu overload steps down to 0 after an overload duration of 180 minutes by taking the transformer out of service

For the same two conditions (a) and (b), Figure 12 illustrates the difference in the hot spot temperatures. For (a), the hot spot temperature will eventually return to 95°C, the hot spot temperature for 1pu current flow at an ambient temperature of 30°C.

Again, for the same two conditions (a) and (b), Figure 13 illustrates the difference in the loss of life.

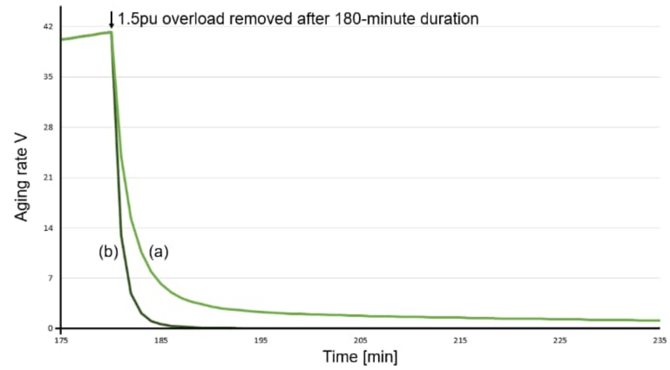


Figure 11: Aging rate V following removal of the 1.5pu overload

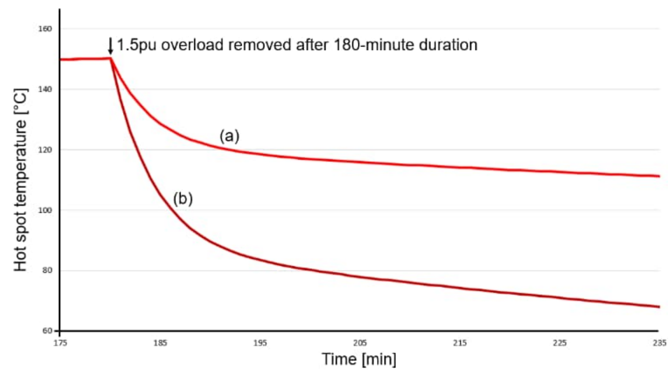


Figure 12: Hot spot temperature following the removal of the 1.5pu overload

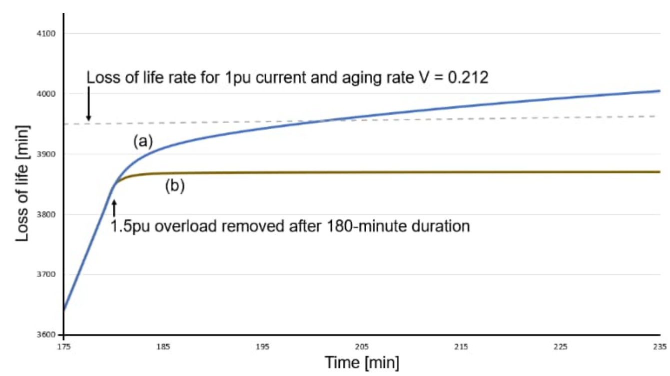


Figure 13: Loss of life following the removal of the 1.5pu overload

A steady state current of 1pu flowing at an ambient temperature of 30°C results in a steady aging rate V of 0.212. This means that for every minute the transformer is in service, 0.212 minutes of life will be lost. This rate of life lost is represented by the dashed line in Figure 13. The (a) plot, after sufficient time has elapsed, will eventually be parallel with the dashed line. The amount of time that needs to elapse for this to happen is more than 900 minutes (more than 15 hours). What this means is that for a 180 minute 1.5pu overload that returns to 1pu current flow, it will take more than an additional 900 minutes for the transformer to return to the pre-overload state (the 1pu current 95°C hot spot temperature and 0.212 loss of life rate).

Finally, to conclude this section, Figures 14 – 16 illustrate the difference in hot spot temperature, aging rate and life lost following a step change from 1pu to 1.5pu with 1.5pu overload duration of (i) 180 minutes, (ii) 120 minutes and (iii) 60 minutes, before a step change back to 1pu.

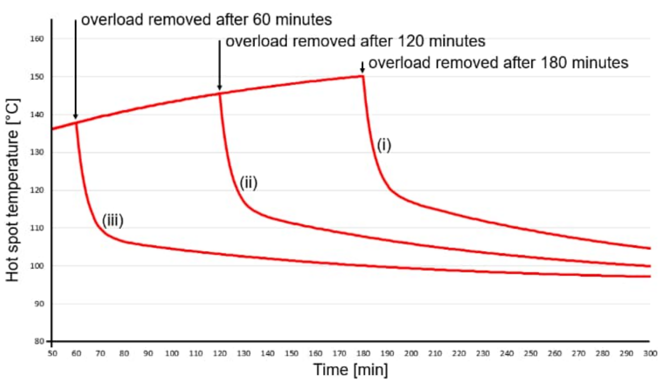


Figure 14: Difference in hot spot temperatures resulting from different overload durations

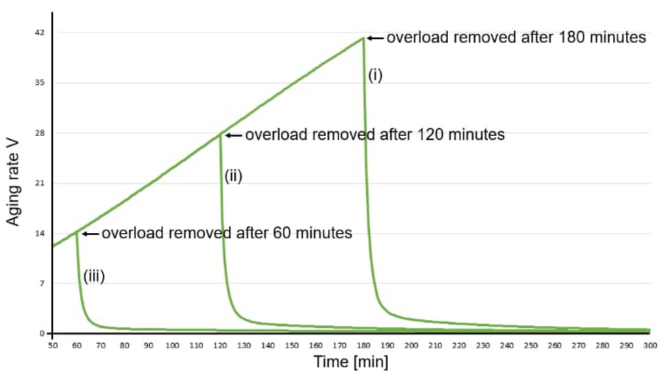


Figure 15: Difference in aging rates resulting from different overload durations

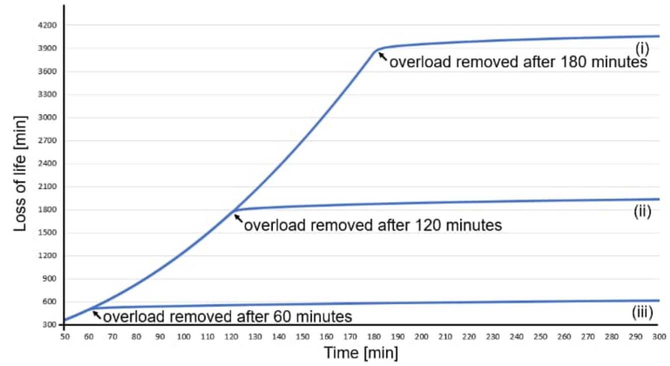


Figure 16: Difference in amount of life lost resulting from different overload durations

As already stated, the above analysis was based on a fixed ambient temperature (30°C), a fixed pre-overload level (1pu), a fixed overload level (1.5pu) and a fixed tap position (tap 3, the rated voltage tap). The next sections look at the influence that variations in these factors have.

VII INFLUENCE OF AMBIENT TEMPERATURE

In this section the influence of ambient temperature is considered. All other conditions remain unchanged. The pre-overload level remains at 1pu, and the overload level remains at 1.5pu.

Table 5 and Figure 17 illustrate the influence of ambient temperature on loss of life for $I_{operate}$ = 1.1pu ($I_{operate}$ = 1.1pu gives a time to operate = overload duration of 22 minutes).

Steady state current before overload		1.0 x rated current
Steady state overload current		1.5 x rated current
$I_{operate}$		1.1 x rated current
$T_{ambient}$ [°C]	Operate time [min]	Loss of life [min]
-30	22	0.1
-20	22	0.5
-10	22	1.6
0	22	4.9
10	22	14.4
20	22	39.5
30	22	103
40	22	259
50	22	619

Table 5: Influence of ambient temperature on loss of life for $I_{operate}$ = 1.1pu

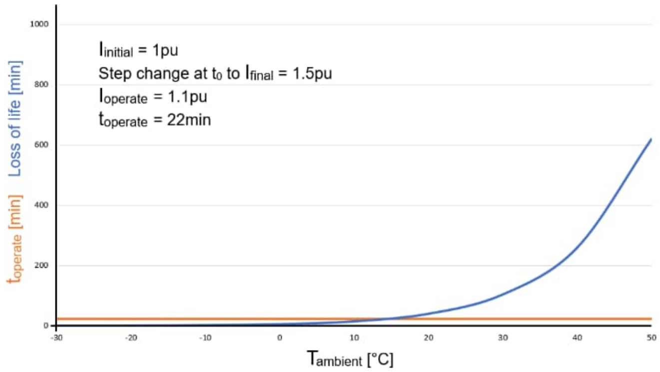


Figure 17: $t_{operate}$ and loss of life for increasing $T_{ambient}$ for $I_{operate}$ = 1.1pu

Table 6 and Figure 18 illustrate the influence of ambient temperature on loss of life for $I_{operate}$ = 1.2pu ($I_{operate}$ = 1.2pu gives a time to operate = overload duration of 52 minutes).

Steady state current before overload		1.0 x rated current
Steady state overload current		1.5 x rated current
$I_{operate}$		1.2 x rated current
$T_{ambient}$ [°C]	Operate time [min]	Loss of life [min]
-30	52	0.7
-20	52	2.2
-10	52	7.1
0	52	21.1
10	52	59.6
20	52	159
30	52	407
40	52	992
50	52	2320

Table 6: Influence of ambient temperature on loss of life for $I_{operate}$ = 1.2pu

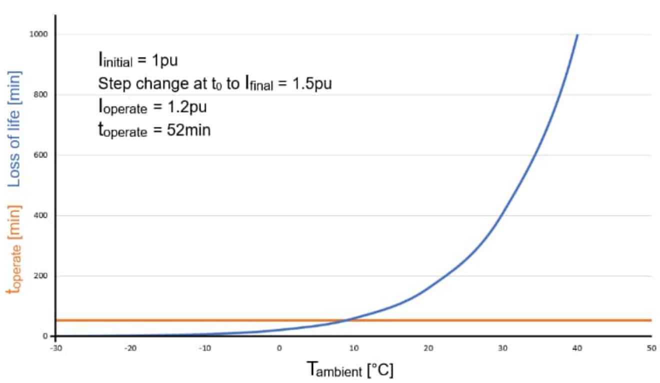


Figure 18: $t_{operate}$ and loss of life for increasing $T_{ambient}$ for $I_{operate}$ = 1.2pu

Table 7 and Figure 19 illustrate the influence of ambient temperature on loss of life for $I_{operate}$ = 1.3pu ($I_{operate}$ = 1.3pu gives a time to operate = overload duration of 96 minutes).

Steady state current before overload		1.0 x rated current
Steady state overload current		1.5 x rated current
$I_{operate}$		1.3 x rated current
$T_{ambient}$ [°C]	Operate time [min]	Loss of life [min]
-30	96	2.3
-20	96	7.5
-10	96	22.9
0	96	66.3
10	96	182
20	96	474
30	96	1180
40	96	2814
50	96	6447

Table 7: Influence of ambient temperature on loss of life for $I_{operate}$ = 1.3pu

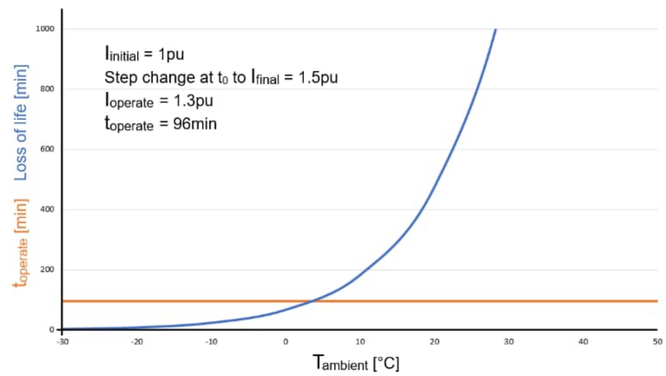


Figure 19: $t_{operate}$ and loss of life for increasing $T_{ambient}$ for $I_{operate}$ = 1.3pu

From Tables 5 – 7 and the plotted graphs in Figures 17 – 19 it can be seen that for very cold ambient temperatures the transformer experiences only negligible loss of life for the 1.5pu overload, even for tripping times of more than an hour and a half (96 minutes).

Figure 20 illustrates the hot spot temperature over time for the 1.5pu overload for different ambient temperatures. With all other conditions unchanged, the difference between the hot spot temperatures is the same as the difference between the ambient temperatures.

Figures 21 and 22 illustrate the aging rate over time for the 1.5pu overload for different ambient temperatures. Figure 22 is a zoom-in of Figure 21 to show more clearly the aging rate at the lower ambient temperatures.

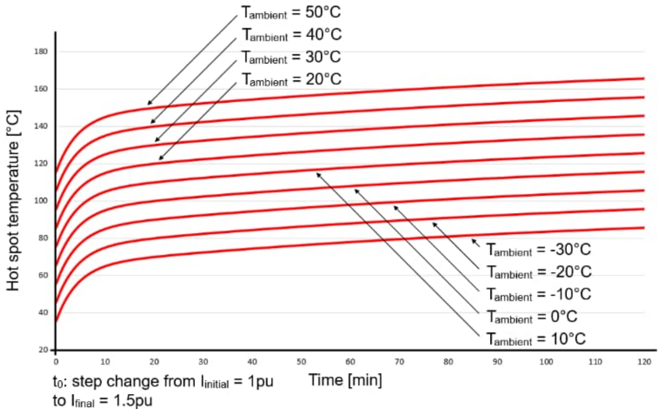


Figure 20: Hot spot temperature over time for different $T_{ambient}$

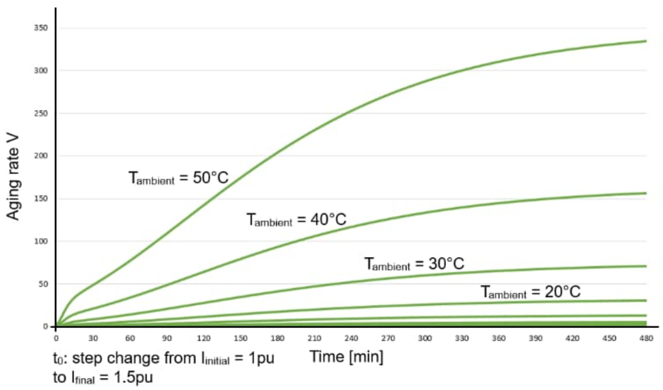


Figure 21: Aging rate over time for different $T_{ambient}$

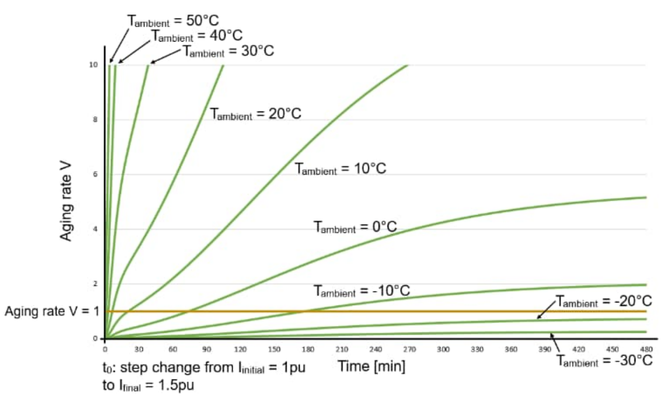


Figure 22: Zoom-in on aging rate over time for different $T_{ambient}$

For ambient temperatures lower than somewhere between -10°C and -20°C the aging rate remains less than 1, even after 8 hours duration of the 1.5pu overload. Therefore the life lost by the transformer during the overload from the overload inception at t_0 remains small.

For an ambient temperature of -10°C the aging rate remains less than 1 for around 3 hours of overload duration. For an ambient temperature of 0°C this time shortens to around 75 minutes of overload duration. For higher ambient temperatures the aging rate exceeds 1 after just very short overload durations, e.g. around 20 minutes for an ambient temperature of 10°C, and around 7 minutes for an ambient temperature of 20°C.

Figure 23 illustrates the life lost by the transformer for increasing duration of the 1.5pu overload at different ambient temperatures.

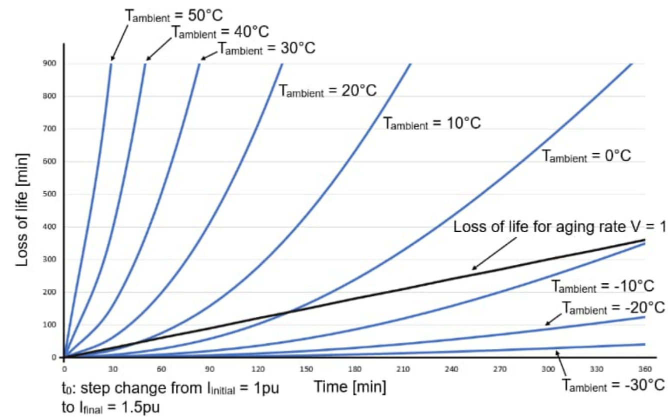


Figure 23: Amount of life lost over time for different $T_{ambient}$

VII INFLUENCE OF LOAD LEVEL PRIOR TO OVERLOAD

In this section the influence of the load level ($I_{initial}$) prior to the overload is considered. All other conditions remain unchanged. The overload level (I_{final}) remains at 1.5pu, and the ambient temperature remains at 30°C.

Figure 24 illustrates the rise in heat content (Θ) to Θ_{final} from different levels of $\Theta_{initial}$. Figure 25 is a zoom-in of Figure 24 to show more clearly the impact $\Theta_{initial}$ has in the time taken for the heat content to reach the $\Theta_{operate}$ level.

Figure 25 shows that for $I_{initial}$ = 1pu to $I_{initial}$ = 0.1pu

- the time taken to reach the $\Theta_{operate}$ level increases, but also that
- the time intervals between the curves at the $\Theta_{operate}$ level get progressively shorter.

Figure 26 illustrates the $t_{operate}$ profile that results due to this, i.e. Figure 26 illustrates $t_{operate}$ as a function of $I_{initial}$.

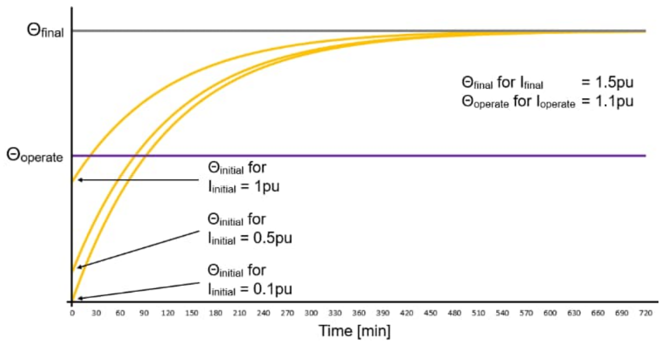


Figure 24: Rise in heat content (Θ) to Θ_{final} from different levels of $\Theta_{initial}$

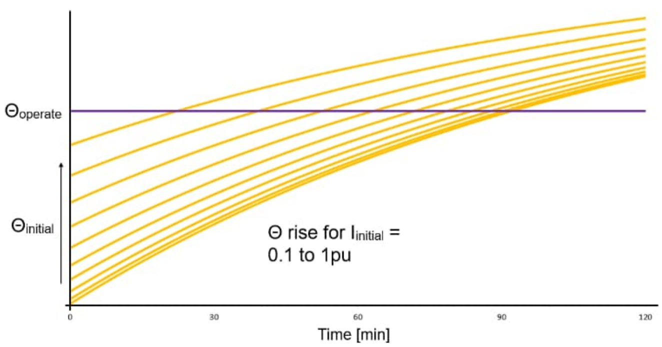


Figure 25: Zoom-in of Figure 24 at the $\Theta_{operate}$ level

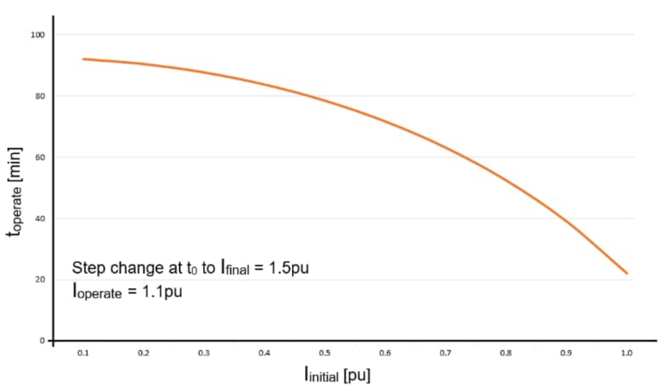


Figure 26: $t_{operate}$ as function of $I_{initial}$

In section VI it was shown that increasing the $I_{operate}$ setting increased the time to operate ($t_{operate}$) of the thermal overload protection, which in turn increased the amount of life lost.

Figure 26 illustrates the impact $I_{initial}$ has on $t_{operate}$, but just for $I_{operate}$ = 1.1pu. Figures 27 and 28 illustrate the impact $I_{initial}$ has on $t_{operate}$, and the amount of life lost, for four different $I_{operate}$ settings (=1.1pu, 1.2pu, 1.3pu and 1.4pu).

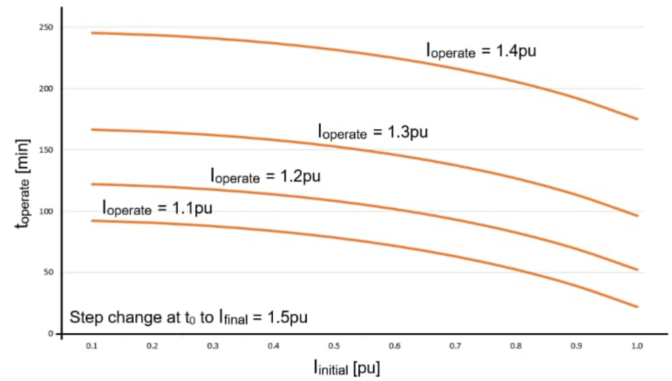


Figure 27: $t_{operate}$ as a function of $I_{initial}$ for different $I_{operate}$

The $t_{operate}$ profiles illustrated in Figure 27 are as expected. The shape of the profiles does not change, but the larger the $I_{operate}$ setting, the longer $t_{operate}$ will become, with increasing difference in the $t_{operate}$ profiles as $I_{operate}$ increases. This can be explained by referring to Figure 25, and imagining the $\Theta_{operate}$ level being increased.

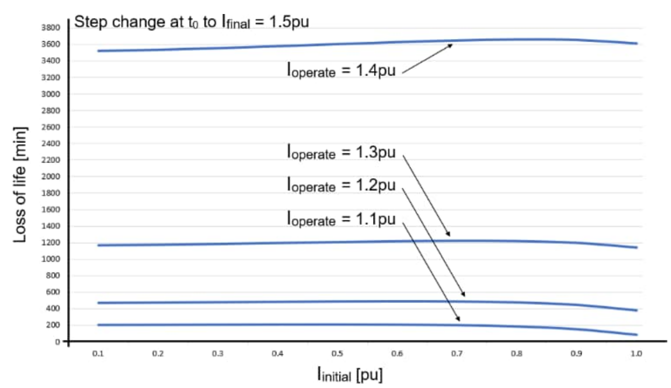


Figure 28: Amount of life lost as a function of $I_{initial}$ for different $I_{operate}$

The amount of life lost illustrated in Figure 28 appears to follow what's already been observed:

- increasing $I_{operate}$ increases $t_{operate}$ and, as expected, increasing $t_{operate}$ increases the amount of life lost
- the increasing difference in the amount of life lost for the increasing $I_{operate}$ is consistent with the increase in $t_{operate}$ as illustrated in Figure 27.

However, delving deeper, and looking at each loss of life profile at an appropriate Y-axis scale for each, it can be observed that, for any given $I_{operate}$ setting, the amount of life lost doesn't increase with increasing $t_{operate}$ (see Figure 27) as $I_{initial}$ decreases from 1pu to 0.1pu.

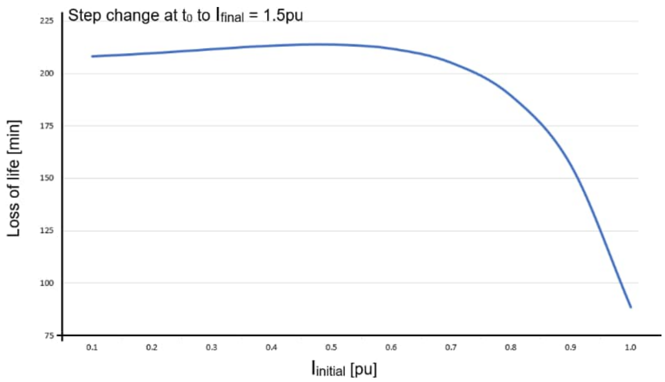


Figure 29: Zoom-in of Figure 28 for $I_{operate}$ = 1.1pu

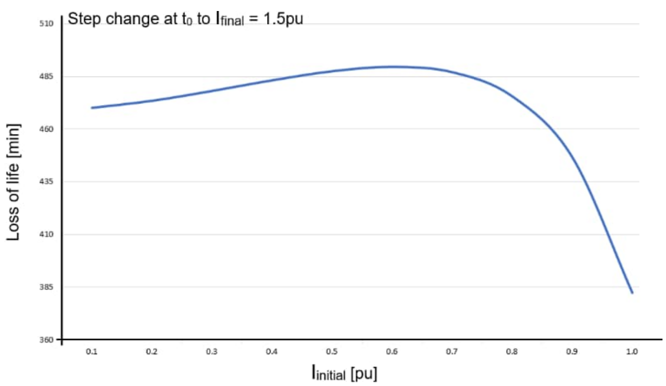


Figure 30: Zoom-in of Figure 28 for $I_{operate}$ = 1.2pu

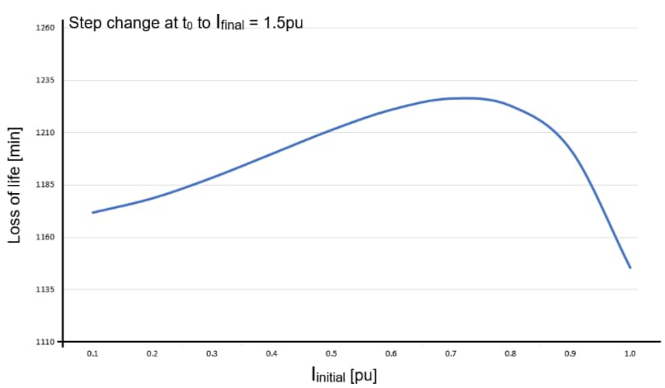


Figure 31: Zoom-in of Figure 28 for $I_{operate}$ = 1.3pu

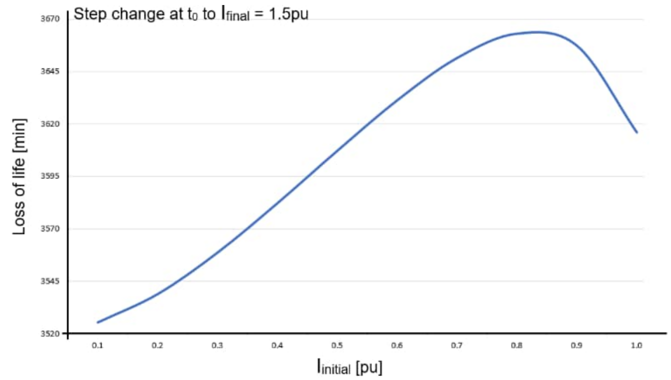


Figure 32: Zoom-in of Figure 28 for $I_{operate}$ = 1.4pu

The topic of this section is the influence of different $I_{initial}$ on the amount of life lost during the overload. Keeping to this, the following observations can be made:

- For $I_{operate}$ = 1.1pu (Figure 29), the percentage difference between the maximum and minimum amount of life lost for different $I_{initial}$ (0.1 to 1pu) is 142% (taking the minimum amount of life lost at $I_{initial}$ = 1.0pu as the base).
- For each increased $I_{operate}$ setting, the percentage difference between the maximum and minimum amount of life lost for different $I_{initial}$ (0.1 to 1pu) reduces significantly. For $I_{operate}$ = 1.4pu (Figure 32), this difference for different $I_{initial}$ reduces to 4% (taking the minimum amount of life lost at $I_{initial}$ = 0.1pu as the base).
- Where the percentage difference between the maximum and minimum amount of life lost is largest (lower $I_{operate}$ setting = 1.1pu), the amount of life lost is still fairly small, and so the large percentage difference is somewhat insignificant.
- However, where amount of life lost increases appreciably (higher $I_{operate}$ settings = 1.3 and 1.4pu), the percentage difference between the maximum and minimum amount of life lost becomes significantly smaller.

The conclusion that can be drawn from the above is that $I_{initial}$ is not a factor that plays a significant role when determining the critical aspects, like how long the transformer can remain in service ($t_{operate}$) with just an acceptable amount of life lost. The maximum expected $I_{initial}$ can be chosen when determining the $I_{operate}$ setting to provide the required operate time.

Knowing how long the transformer can, or must, stay in service ($t_{operate}$), a value for $I_{operate}$ can be determined that yields the required $t_{operate}$. The value for $I_{operate}$, based on the required $t_{operate}$, is given by the following equation:

$$I_{operate} = \sqrt{\frac{I_{initial}^2 - (1 - e^{\frac{t_{operate}}{\tau}})*I_{final}^2}{e^{\frac{t_{operate}}{\tau}}}} \qquad \text{Equation 9}$$

for $I_{initial} < I_{operate} < I_{final}$

To get $I_{operate}$ in pu, the value calculated by Equation 9 must be divided by the 1pu base current in Amperes.

If the $I_{operate}$ setting is based on the required operate time for $I_{initial}$ = 1pu, the operate time will be longer (the transformer will stay in service longer) for a lesser $I_{initial}$, with very limited impact on loss of life.

Steady state overload current	1.5 x rated current	
Required operate time based on	1.0 x rated current	steady state current before overload
Compare performance for actual	0.5 x rated current	steady state current before overload

Required operate time [min]	Operate current setting [per unit of rated current] to get required operate time for $I_{initial}$ = 1pu	Loss of life [min] for $I_{initial}$ = 1pu	Actual operate time [min] for $I_{initial}$ = 0.5pu	Loss of life [min] for $I_{initial}$ = 0.5pu
30	1.130	169	86	284
60	1.221	516	116	607
90	1.288	1049	146	1112
120	1.338	1788	176	1820
150	1.375	2737	206	2740
180	1.404	3888	236	3863

Table 8: $I_{operate}$ for required $t_{operate}$ based on $I_{initial}$ = 1pu

However, if the $I_{operate}$ setting is based on the required operate time for a lower $I_{initial}$, the operate time will be shorter (the transformer will be taken out of service sooner) for a larger $I_{initial}$.

By basing the $I_{operate}$ setting on a lower value of $I_{initial}$, care will be needed to check that the calculated setting is not too low (see Table 9 row 1), or that it doesn't fail to comply with PRC-023 (see Table 9 row 2).

Steady state overload current	1.5 x rated current	
Required operate time based on	0.5 x rated current	steady state current before overload
Compare performance for actual	1.0 x rated current	steady state current before overload

Required operate time [min]	Operate current setting [per unit of rated current] to get required operate time for $I_{initial}$ = 0.5pu	Loss of life [min] for $I_{initial}$ = 0.5pu	Actual operate time [min] for $I_{initial}$ = 1pu	Loss of life [min] for $I_{initial}$ = 1pu
30	0.832	28	x	x
60	1.018	121	4	4
90	1.142	317	34	196
120	1.231	663	64	561
150	1.295	1194	94	1113
180	1.343	1931	124	1873

Table 9: $I_{operate}$ for required $t_{operate}$ based on $I_{initial}$ = 0.5pu

Before ending this section it's worth noting one further observation. The same operate time ($t_{operate}$), but with $I_{operate}$ and $I_{initial}$ different, doesn't result in the same amount of life lost. For example:

- $I_{operate}$ = 1.2pu, and $I_{initial}$ = 1pu. For the 1.5pu overload, $t_{operate}$ = 52 minutes. Amount of life lost = 382 minutes.
  $I_{operate}$ = 1.1pu, and $I_{initial}$ = 0.80pu. For the 1.5pu overload, $t_{operate}$ = 52 minutes. Amount of life lost = 189 minutes.
- $I_{operate}$ = 1.3pu, and $I_{initial}$ = 1pu. For the 1.5pu overload, $t_{operate}$ = 96 minutes. Amount of life lost = 1145 minutes.
  $I_{operate}$ = 1.2pu, and $I_{initial}$ = 0.66pu. For the 1.5pu overload, $t_{operate}$ = 96 minutes. Amount of life lost = 489 minutes.

The above is consistent with what is illustrated in Figure 28, and also Figures 29 to 32. The higher the $I_{operate}$ setting (and $I_{initial}$ to get the same $t_{operate}$), the higher the current flow for the same amount of time, hence the higher amount of life lost. This is illustrated in Figure 33.

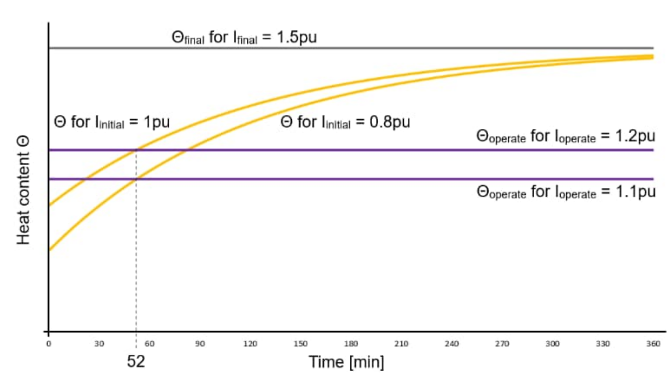


Figure 33: Same $t_{operate}$ for different combinations of $I_{operate}$ and $I_{initial}$

VII INFLUENCE OF OVERLOAD LEVEL

In this section the influence of the overload level (I_{final}) is considered. All other conditions remain unchanged. The load level ($I_{initial}$) prior to the overload remains at 1pu, and the ambient temperature remains at 30°C.

Figure 34 illustrates the rise in heat content (Θ) from $\Theta_{initial}$ to different levels of Θ_{final}. Figure 35 is a zoom-in of Figure 34 to show more clearly the impact Θ_{final} has in the time taken for the heat content to reach the $\Theta_{operate}$ level.

Figure 35 shows that for I_{final} = 1.2pu to I_{final} = 2pu

- the time taken to reach the $\Theta_{operate}$ level decreases, but also that
- the time intervals between the curves at the $\Theta_{operate}$ level get progressively shorter.

Figure 36 illustrates the $t_{operate}$ profile that results due to this, i.e. Figure 36 illustrates $t_{operate}$ as a function of I_{final}.

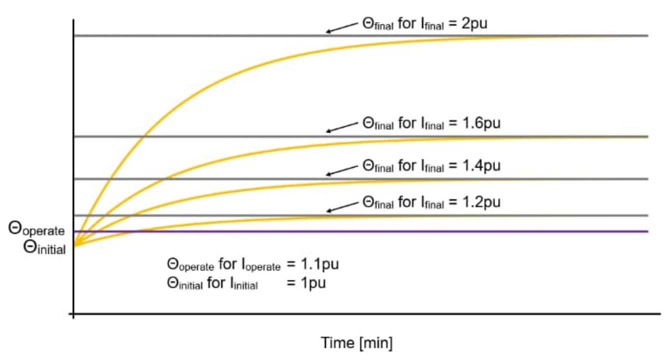


Figure 34: Rise in heat content (Θ) to different levels of Θ_{final} from $\Theta_{initial}$

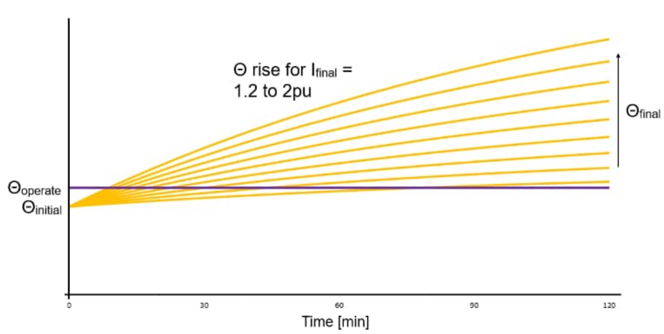


Figure 35: Zoom-in of Figure 34 at the $\Theta_{operate}$ level

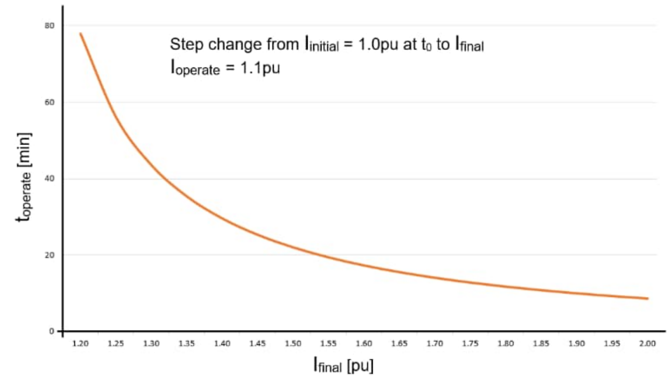


Figure 36: $t_{operate}$ as a function of I_{final}

It was shown in section VI that increasing the $I_{operate}$ setting increased the time to operate ($t_{operate}$) of the thermal overload protection, which in turn increased the amount of life lost.

Figure 36 illustrates the impact I_{final} has on $t_{operate}$, but just for $I_{operate}$ = 1.1pu. Figures 37 to 41 illustrate the impact I_{final} has on $t_{operate}$, and the amount of life lost, for four different $I_{operate}$ settings (= 1.1pu, 1.2pu, 1.3pu and 1.4pu).

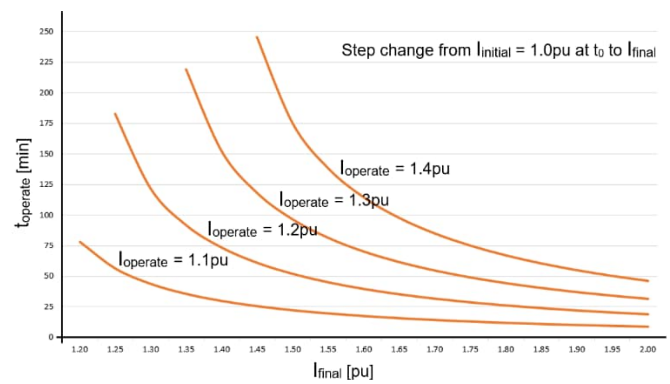


Figure 37: $t_{operate}$ as a function of I_{final} for different $I_{operate}$

The $t_{operate}$ profiles illustrated in Figure 37 are as expected. The shape of the profiles does not change, but the larger the $I_{operate}$ setting, the longer $t_{operate}$ will become. Note that for any given $I_{operate}$, I_{final} must be larger to get an operation.

Figures 38 to 41 illustrate the amount of life lost for different $I_{operate}$. Each loss of life profile is illustrated at an appropriate Y-axis scale.

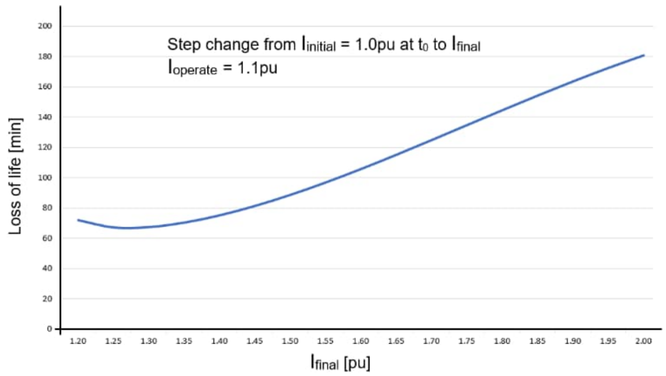


Figure 38: Amount of life lost as a function of I_{final} for $I_{operate}$ = 1.1pu

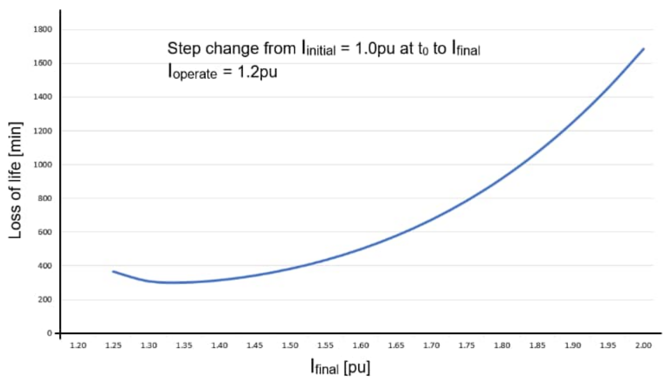


Figure 39: Amount of life lost as a function of I_{final} for $I_{operate}$ = 1.2pu

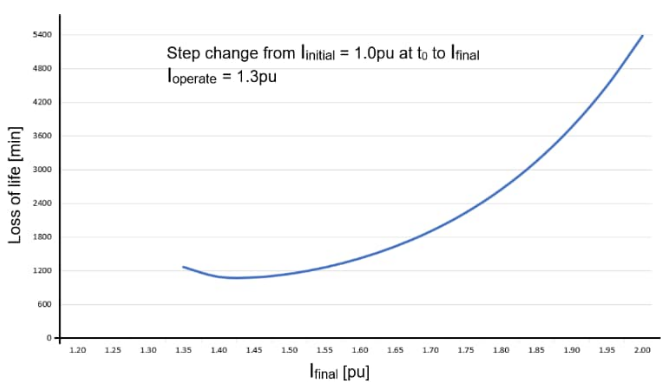


Figure 40: Amount of life lost as a function of I_{final} for $I_{operate}$ = 1.3pu

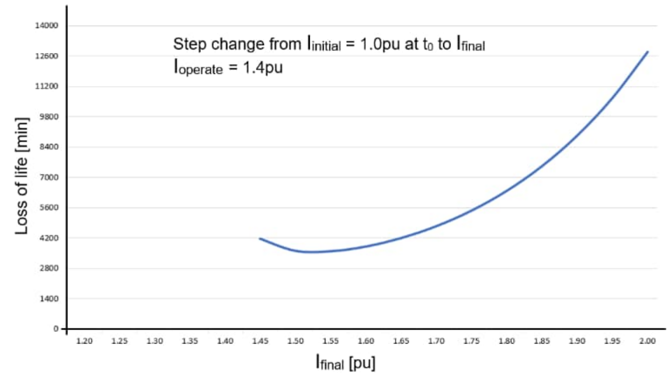


Figure 41: Amount of life lost as a function of I_{final} for $I_{operate}$ = 1.4pu

Keeping to the topic of this section, the following observations can be made:

- The amount of life lost increases significantly as $I_{operate}$ increases.
- For each $I_{operate}$, the amount of life lost has maximum value at the highest I_{final} (= 2pu), with a steep upward trend at this point.
- For $I_{operate}$ = 1.1pu, the loss of life is not too significant, even for I_{final} = 2pu. However, the operate times are not that long. This may necessitate that a higher $I_{operate}$ setting needs to be selected to meet the required time for which the transformer must remain in service. A higher $I_{operate}$ setting results in an increased amount of life lost.

If the $I_{operate}$ setting is based on achieving the required operate time for I_{final} = ,say, 1.5pu, the operate time will be shorter (the transformer will be removed from service sooner) for a larger I_{final}, with a very limited impact on the amount of life lost. This is illustrated in Table 10. The significantly reduced operate times for larger I_{final} could well be deemed acceptable for such high levels of overload.

However, if I_{final} is less than the I_{final} on which the $I_{operate}$ setting was based, the operate time will be longer (the transformer will stay in service longer). This is illustrated in Table 11. Note however, that to get operation $I_{final} > I_{operate}$.

Steady state current before overload				1.0 x rated current		
$I_{operate}$ based on I_{final} =				1.5 x rated current		
Required operate time [min] based on I_{final} = 1.5pu	Operate current setting [per unit of rated current]	Loss of life [min] for I_{final} = 1.5pu	Actual operate time [min] for I_{final} = 1.65pu	Loss of life [min] for I_{final} = 1.65pu	Actual operate time [min] for I_{final} = 1.8pu	Loss of life [min] for I_{final} = 1.8pu
15	1.071	56	11	65	8	95
30	1.130	169	21	259	16	366
60	1.221	516	40	795	30	1303
90	1.288	1049	58	1508	42	2506
120	1.338	1788	74	2422	52	3996
150	1.375	2737	88	3440	61	5351
180	1.404	3888	100	4489	68	6963
210	1.426	5223	110	5494	74	8354
240	1.443	6721	118	6504	79	9642
270	1.455	8358	126	7360	83	10759
300	1.465	10112	132	8143	86	11650

Table 10: Impact of I_{final} > I_{final} on which $I_{operate}$ was based

Steady state current before overload					1.0 x rated current	
$I_{operate}$ based on I_{final} =					1.5 x rated current	
Required operate time [min] based on I_{final} = 1.5pu	Operate current setting [per unit of rated current]	Loss of life [min] for I_{final} = 1.5pu	Actual operate time [min] for I_{final} = 1.35pu	Loss of life [min] for I_{final} = 1.35pu	Actual operate time [min] for I_{final} = 1.2pu	Loss of life [min] for I_{final} = 1.2pu
15	1.071	56	24	42	49	40
30	1.130	169	49	121	119	128
60	1.221	516	109	409	X	X
90	1.288	1049	194	1054	X	X
120	1.338	1788	388	3171	X	X
150	1.375	2737	X	X	X	X
180	1.404	3888	X	X	X	X
210	1.426	5223	X	X	X	X
240	1.443	6721	X	X	X	X
270	1.455	8358	X	X	X	X
300	1.465	10112	X	X	X	X

Table 11: Impact of I_{final} < I_{final} on which $I_{operate}$ was based

The conclusion that can be drawn from the above is that a good approach would be to base the $I_{operate}$ setting on a moderately high I_{final} (say = 1.5pu, or other level corresponding to the average expected maximum overload). Basing the $I_{operate}$ setting on a too high I_{final} is not optimal because

- to get operation I_{final} > $I_{operate}$, so an overly high $I_{operate}$ would not cover lower overload levels, and
- the amount of life lost would be significantly higher.

The above two points are illustrated in Table 12.

Steady state current before overload				1.0 x rated current
Required operate time [min]	Operate current setting [per unit of rated current] based on I_{final} = 1.5pu	Loss of life [min] for I_{final} = 1.5pu	Operate current setting [per unit of rated current] based on I_{final} = 1.8pu	Loss of life [min] for I_{final} = 1.8pu
15	1.071	56	1.124	366
30	1.130	169	1.223	1388
60	1.221	516	1.372	5351
90	1.288	1049	1.477	12910
120	1.338	1788	1.554	25216
150	1.375	2737	1.612	43039
180	1.404	3888	1.655	66694
210	1.426	5223	1.688	96084
240	1.443	6721	1.714	130821
270	1.455	8358	1.733	170337
300	1.465	10112	1.748	213993

Table 12: Comparison of amount of life lost for $I_{operate}$ based on I_{final} = 1,5pu and I_{final} = 1.8pu

From Table 12 it can be seen that basing the $I_{operate}$ setting, to achieve a required $t_{operate}$, on I_{final} = 1.8pu, many significant but lesser overloads will not be covered. Also, for an actual 1.8pu overload, the amount of life lost when basing the $I_{operate}$ setting on I_{final} = 1.8pu will be significantly more than for an actual 1.8pu overload, but with the $I_{operate}$ setting based on I_{final} = 1.5pu. Of course, for the latter the time to operate will also be much shorter for the 1.8pu overload than if $I_{operate}$ were based on I_{final} = 1.8pu. Tables 10 and 12 illustrate this.

As with the previous section, before ending this section it's worth noting one further observation. The same operate time ($t_{operate}$), but with $I_{operate}$ and I_{final} different, doesn't result in the same amount of life lost. For example (for $I_{initial}$ = 1pu):

- $I_{operate}$ = 1.3pu, and I_{final} = 2pu. $t_{operate}$ = 31 minutes. Amount of life lost = 5382 minutes.
  $I_{operate}$ = 1.2pu, and I_{final} = 1.71pu. $t_{operate}$ = 31 minutes. Amount of life lost = 687 minutes.
- $I_{operate}$ = 1.4pu, and I_{final} = 2pu. $t_{operate}$ = 46 minutes. Amount of life lost = 12793 minutes.
  $I_{operate}$ = 1.3pu, and I_{final} = 1.78pu. $t_{operate}$ = 46 minutes. Amount of life lost = 2446 minutes.

The above is consistent with what is illustrated in Figures 39 to 41. The higher the $I_{operate}$ setting (and I_{final} to get the same $t_{operate}$), the higher the current flow for the same amount of time, hence the higher the amount of life lost. This is illustrated in Figure 33.

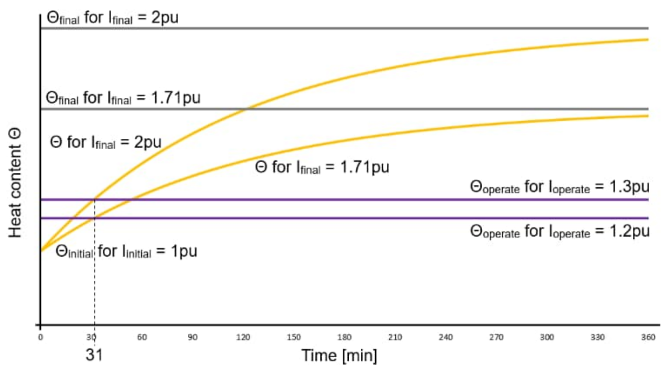


Figure 42: Same $t_{operate}$ for different combinations of $I_{operate}$ and I_{final}

VII INFLUENCE OF TAP POSITION DURING OVERLOAD

For the transformer on which this paper is based, the influence of tap position has a negligible influence. This is because the load to no load loss ratio does not vary much over the tap range.

Steady state current before overload			1.0 x rated current
Steady state overload current			1.5 x rated current
Elapsed time [min] from current step change	Loss of life [min] from current step change		
	Rated voltage tap (3)	High voltage tap (1)	Low voltage tap (5)
10	23	23	23
20	82	82	82
30	160	160	160
40	255	255	256
50	369	368	370
60	502	501	503
70	655	654	658
80	830	829	834
90	1028	1026	1033
100	1248	1246	1255
110	1492	1489	1500
120	1760	1755	1769
150	2702	2694	2719
180	3846	3835	3874
210	5176	5159	5215
240	6669	6646	6723
270	8301	8271	8372
300	10052	10014	10141
330	11899	11853	12007
360	13825	13771	13954
390	15815	15751	15965
420	17855	17782	18028
450	19936	19853	20132
480	22049	21956	22268
510	24187	24084	24430
540	26345	26232	26611

Table 13: Impact of tap position on loss of life

VIII APPLICATION CONSIDERATIONS

In previous sections it was determined which values for $I_{initial}$ and I_{final} should preferably be used in the calculation of $I_{operate}$.

The dilemma here is that to achieve the longer operate times, to maximize the amount of time the transformer will stay in service, requires a larger $I_{operate}$ setting. However, the larger the $I_{operate}$ setting, the higher the level of overload that won't be covered.

The first step is to decide how long the transformer must remain the service for what level of overload. Let's say that the requirement is that the transformer must remain in service for 180 minutes (3 hours) for a 1.5pu overload. Taking I_{final} = 1.5pu, $I_{initial}$ = 1pu, and $t_{operate}$ = 180 minutes, the calculated value for $I_{operate}$ is 1.404pu. The amount of life lost during the 180 minutes of 1.5pu overload will be 3888 minutes. This is deemed to be acceptable to keep the transformer in service for the 180 minutes. With the $I_{operate}$ setting = 1.404pu, this setting is too large to get operation for lower levels of overload (e.g. 1.2pu to 1.404pu).

The next step then is to decide what is the lowest overload level for which, if it persists, the transformer must eventually be taken out of service. Let's say that the lowest overload level for which the transformer must eventually be tripped is 1.2pu. To account for this a definite time overcurrent function (51) can be added.

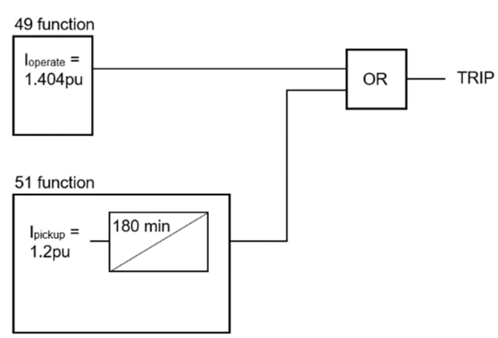


Figure 43: Combination of 49 and 51 functions to get a trip

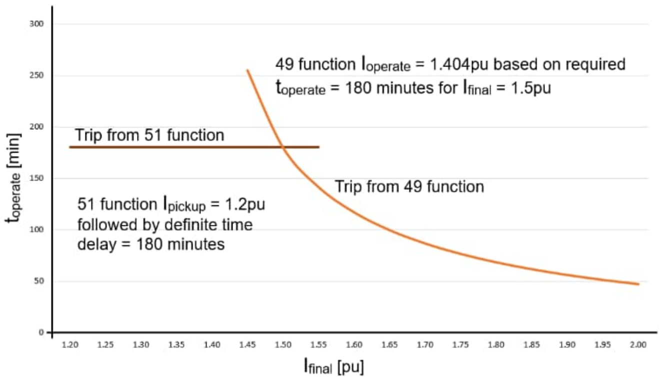


Figure 44: $t_{operate}$ from combination of 49 and 51 functions

From Figure 44 it can be seen that for overloads from 1.2pu to 1.5pu the 51 function will operate before the 49 function and will issue a trip after the definite time of 180 minutes. However, for overloads ≥ 1.5pu, operation from the 49 function will occur before the 51 function, and so from this point on the transformer will be tripped by the 49 function in accordance with the required operate time and $I_{operate}$ setting.

As discussed in section VI, the prevailing ambient temperature plays a significant role in the amount of life lost.

Steady state current before overload			1.0 x rated current			
Steady state overload current			1.5 x rated current			
$I_{operate}$ [pu]	$t_{operate}$ [min]	$T_{ambient}$ = -30°C	$T_{ambient}$ = -10°C	$T_{ambient}$ = 10°C	$T_{ambient}$ = 30°C	$T_{ambient}$ = 50°C
		Loss of life [min]	Loss of life [min]	Loss of life [min]	Loss of life [min]	Loss of life [min]
1.10	22	0	2	14	103	619
1.15	36	0	4	31	215	1255
1.20	52	1	7	60	407	2320
1.25	72	1	13	103	688	3849
1.30	96	2	23	182	1180	6447
1.35	129	4	42	320	2020	10777
1.40	175	9	82	602	3682	19116
1.45	256	21	181	1285	7578	38137

Table 14: Comparison of life lost based on $T_{ambient}$

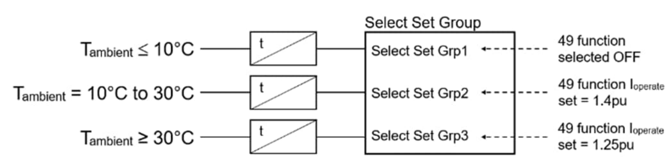
a) No input of ambient temperature is connected to the relay

Under these circumstances the setting for $I_{operate}$ can be based on average expected maximum ambient temperature at the time of an overload. Should the overload occur with a higher ambient temperature the operate time will be the same, but the loss of life will be more. Similarly, should the overload occur with a lower ambient temperature the operate time will again be the same, but the loss of life will be less.

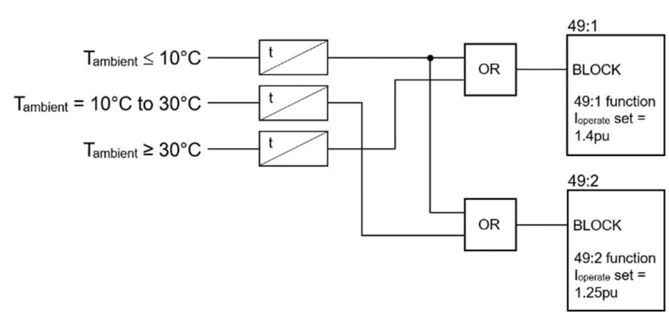
b) Input of ambient temperature is connected to the relay

Under these circumstances it is possible to categorize the ambient temperature into two or more ranges. This can be done using either multiple settings groups, or multiple instances of the thermal overload (49) protection function. As an example, categorize the measured ambient temperature input into three ranges:
≤ 10°C; 10°C to 30°C; ≥ 30°C

- For ambient temperatures ≤ 10°C no thermal overload protection is required.
- For ambient temperatures 10°C to 30°C, set $I_{operate}$ = 1.40pu (based on Table 14 for this example). With this setting an overload of 1.5pu will be tripped in 175 minutes with a resulting 602 to 3682 minutes of transformer life lost depending on the actual ambient temperature.
- For ambient temperatures ≥ 30°C, set $I_{operate}$ = 1.25pu. With this setting an overload of 1.5pu will be tripped in 72 minutes with a resulting 688 to 3849 minutes of transformer life lost depending on the actual ambient temperature. More transformer life will be lost for ambient temperatures > 50°C.



a) Using multiple settings groups



b) Using multiple instances of 49 function

Figure 45 (a) and (b): Possible 3-range ambient temperature solution when ambient temperature is connected to the relay

IX CONCLUSION

In the past, utility application of transformers in their systems did not have to account for unknown overload circumstances since the power grid loads were well known. Overloads arose due to network issues, e.g. line or transformer outages. Operator action could potentially solve these. By following company guidelines and policy, the operator would decide if and when to disconnect the transformer from service.

However, today's power grid is moving to a distributed source/load architecture and the overload contingencies are always evolving. Challenges faced by DER and EV charging deployments bring unknown loading profiles not experienced in the typical power grid.

Although a "necessary evil", the cost of overloading transformers can be quantified as the amount of transformer life lost based on the level and duration of the overload.

Use of the thermal overload protection function could be key in protecting critical transformer assets, which have even longer lead times today.

This paper has shown that settings can be applied to the transformer overload protection function that can maximize the time the transformer will remain in service before being tripped, and also keep the amount of life lost to within acceptable limits. The length of time the transformer can be kept in service with the amount of life lost kept to within acceptable limits far exceeds the requirements of PRC-023.

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