Dynamic thermal modeling and overload testing for optimization of transformer loadability in the context of energy transition

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P. Picher, S. Proulx, C. Tissot, A. Mailhot

Hydro Québec

Canada

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Outline of the paper / presentation

1. Introduction
2. Loading guide equations
3. Extended temperature-rise tests
4. Parametric study of the IEC 60076-7 equations
5. Oil and winding exponents estimation from extended temperature-rise tests
6. Parameters estimation from field measurements
7. Conclusion

Introduction

Context

The energy transition will increase the **thermal stress** on the aging electrical infrastructure

Transformers define substation **power transit capacity**

An increase of power transit capacity could require the **addition of a power transformer** in an existing substation, or the implementation of an **entire new substation**, which can be **very expensive measures**

Scope of our study

To improve our knowledge regarding the prediction of transformer temperature in short-term and long-term **emergency loading scenarios**

To take the best **decisions** regarding transformer asset management **in the context of the energy transition**

Loading guides

IEEE C57.91 – 1995 (now in revision)

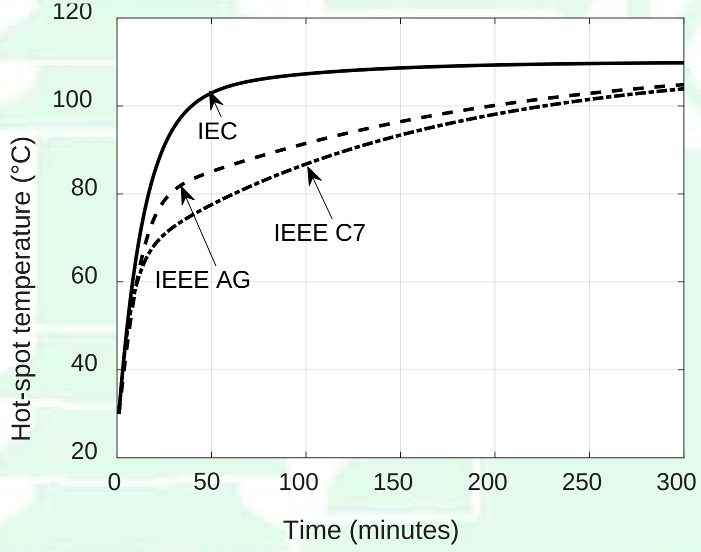
Clause 7 does not model the 'thermal overshoot'

Annex G uses physics-based modeling, including oil viscosity effect and the variation of DC, eddy and stray losses with temperature

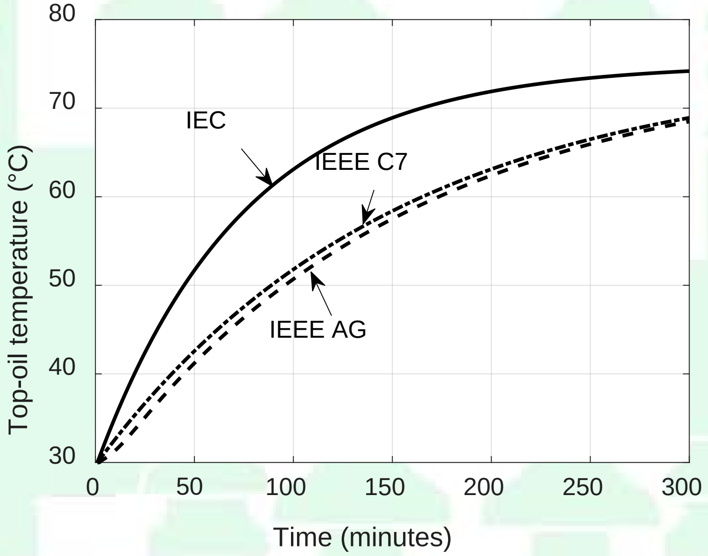
IEC 60076-7 - 2017

Uses a simplified mathematical representation based on observed data

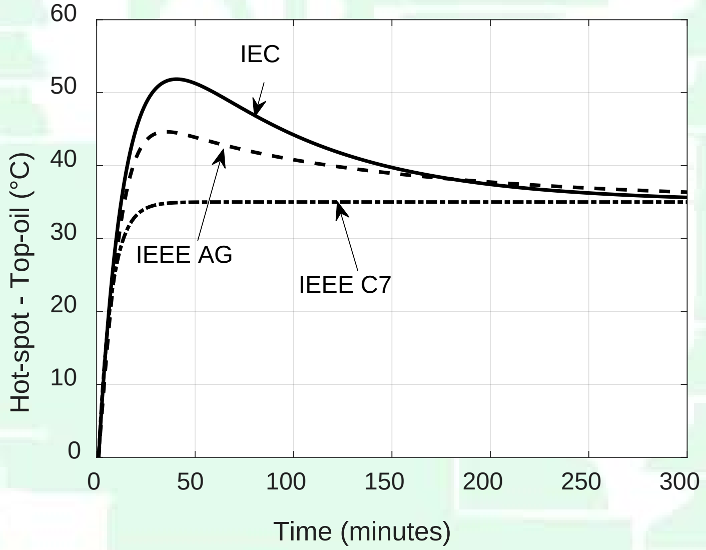
Hot-spot temperature



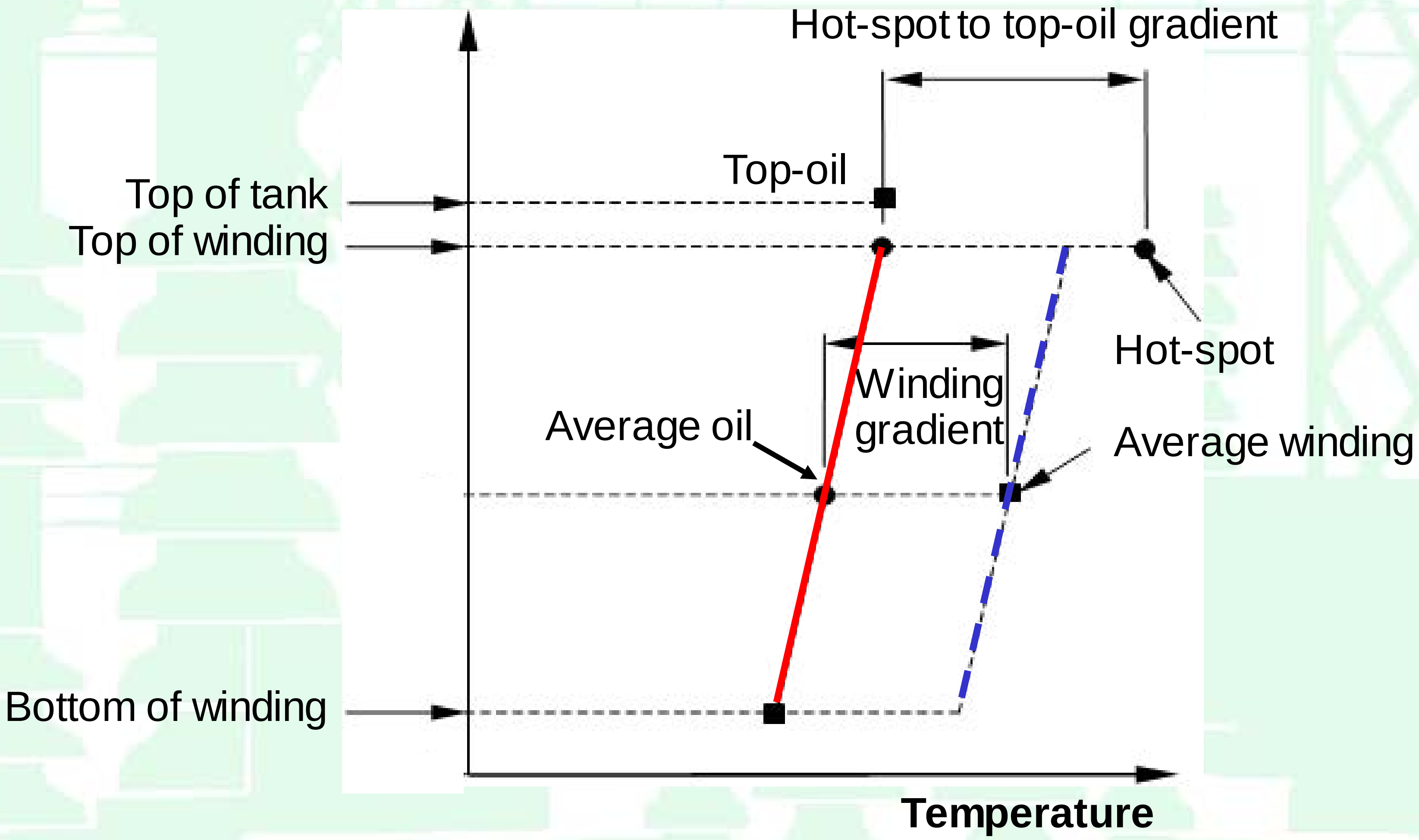
Top-oil temperature



Hot-spot to top-oil gradient



Simplified thermal diagram



IEC 60076-7 loading guide parameters

Input parameters			
θ_a	Ambient temperature	K	Load

↓

Output parameters			
θ_h	Hot-spot temperature	θ_o	Top-oil temperature

x	Exponential power of total losses versus top-oil (in tank) temperature rise (oil exponent)
y	Exponential power of current versus winding temperature rise (winding exponent)
R	Ratio of load losses at rated current to no-load losses at rated voltage
τ_o, τ_w	Oil and winding time constant
$\Delta\theta_{or}$	Top-oil (in tank) temperature rise in steady state at rated losses (no-load losses + load losses)
$\Delta\theta_{hr} = Hg_r$	Hot-spot-to-top-oil (in tank) gradient at rated current
k_{11}, k_{21} k_{22}	Thermal model constants

IEC 60076-7 loading guide equations

Differential equations

$$\theta_h = \theta_o + \Delta\theta_h$$

$$\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) = k_{11}\tau_o \times \frac{d\theta_o}{dt} + [\theta_o - \theta_a]$$

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2}$$

$$k_{21} \times K^y \times (\Delta\theta_{hr}) = k_{22} \times \tau_w \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1}$$

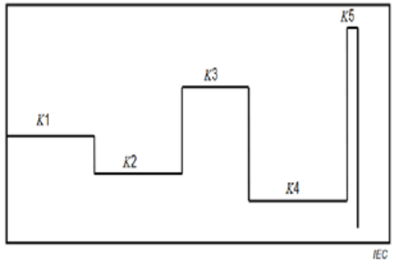
$$(k_{21}-1) \times K^y \times (\Delta\theta_{hr}) = (\tau_o / k_{22}) \times \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2}$$

Exponential equations solution

$$\theta_o(t) = \theta_a + \Delta\theta_{oi} + \left\{\Delta\theta_{or} \times \left[\frac{1+R\times K^2}{1+R}\right]^x - \Delta\theta_{oi}\right\} \times \left(1 - e^{(-t)/(k_{11}\times\tau_o)}\right)$$

$$\Delta\theta_{h1}(t) = \Delta\theta_{h1_i} + \left\{k_{21} Hg_r K^y - \Delta\theta_{h1_i}\right\} \times \left(1 - e^{(-t)/(k_{22}\times\tau_w)}\right)$$

$$\Delta\theta_{h2}(t) = (k_{21}-1) Hg_r K^y + \left\{\Delta\theta_{h2_i} - (k_{21}-1) Hg_r K^y\right\} \times e^{(-t)/(\tau_o/k_{22})}$$



Difference equations solution

$$D\theta_o = \frac{Dt}{k_{11}\tau_o}\left[\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) - [\theta_o - \theta_a]\right]$$

$$D\Delta\theta_{h1} = \frac{Dt}{k_{22}\tau_w} \times \left[k_{21} \times \Delta\theta_{hr} K^y - \Delta\theta_{h1}\right]$$

$$D\Delta\theta_{h2} = \frac{Dt}{(1/k_{22})\tau_o} \times \left[(k_{21}-1) \times \Delta\theta_{hr} K^y - \Delta\theta_{h2}\right]$$

Recommended parameters

The parameters considered for the thermal modeling are essential for the determination of the short-term and long-term emergency overloading

The recommended parameters differs from one standard to the other, and they are different from a transformer to the other

	IEC 60076-7 - 2017			IEEE Std C57.91 - 1995		
	ONAF	OFAF	ODAF	ONAF	OFAF	ODAF
Oil exponent x	0.8	1.0	1.0	0.9	0.9	1.0
Winding exponent y	1.3	1.3	2.0	1.6	1.6	2.0

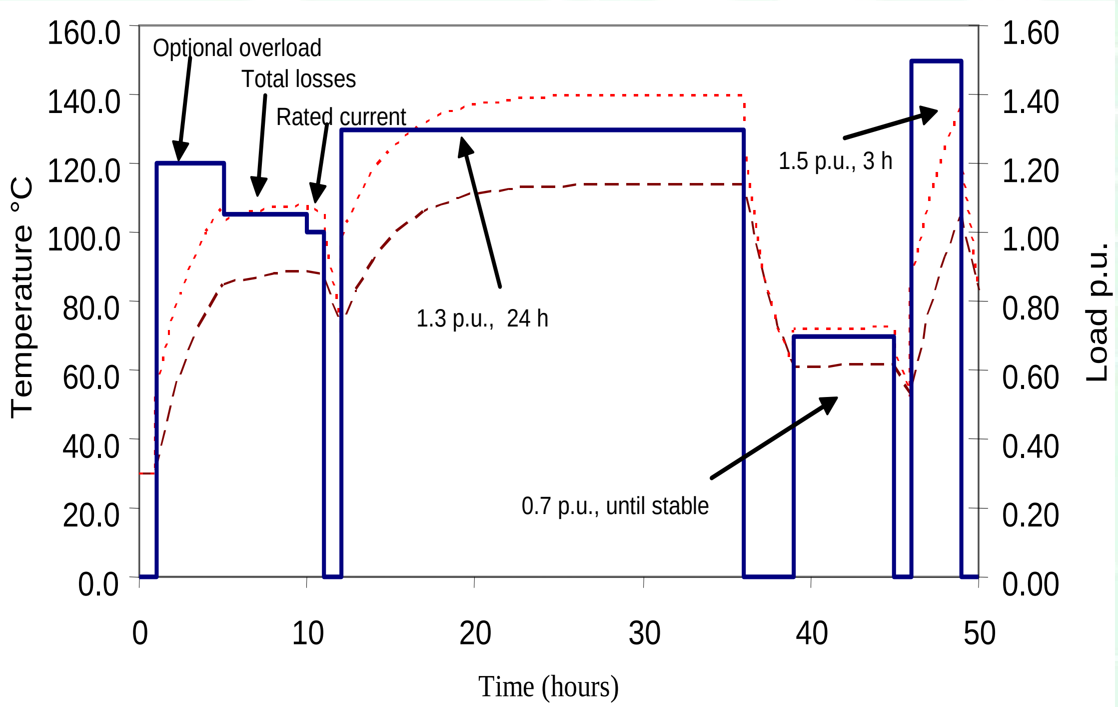
"Reference transformer" for this study

Extended temperature-rise tests

Load profile

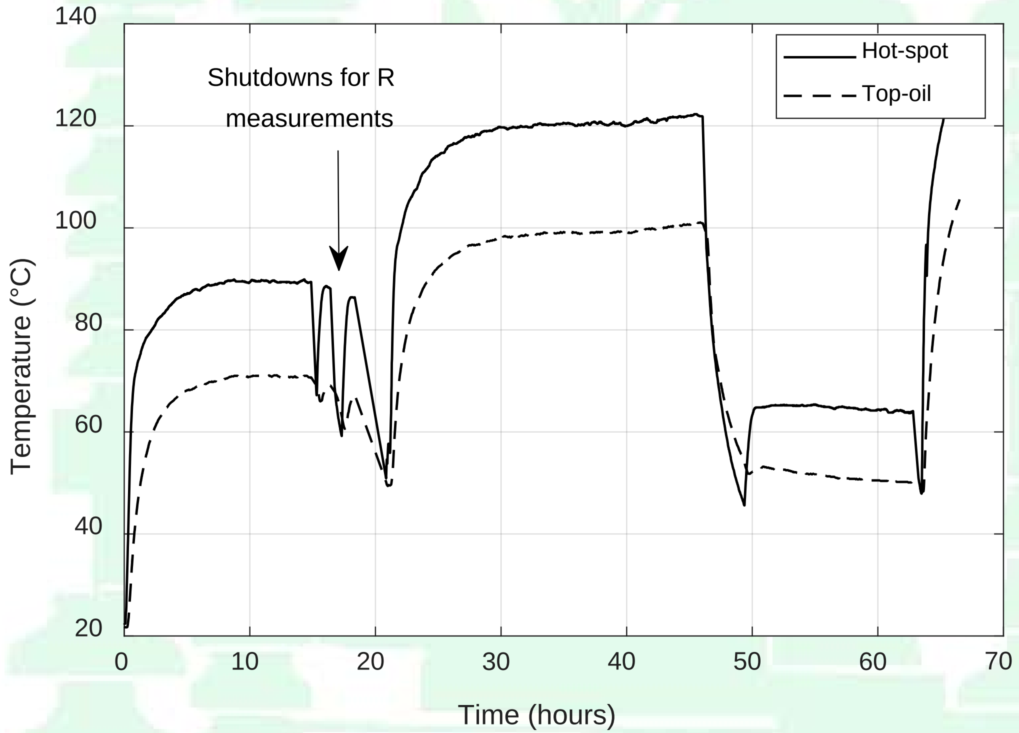
To demonstrate the overload capacity

Since 1991, more than 60 transformers have been tested



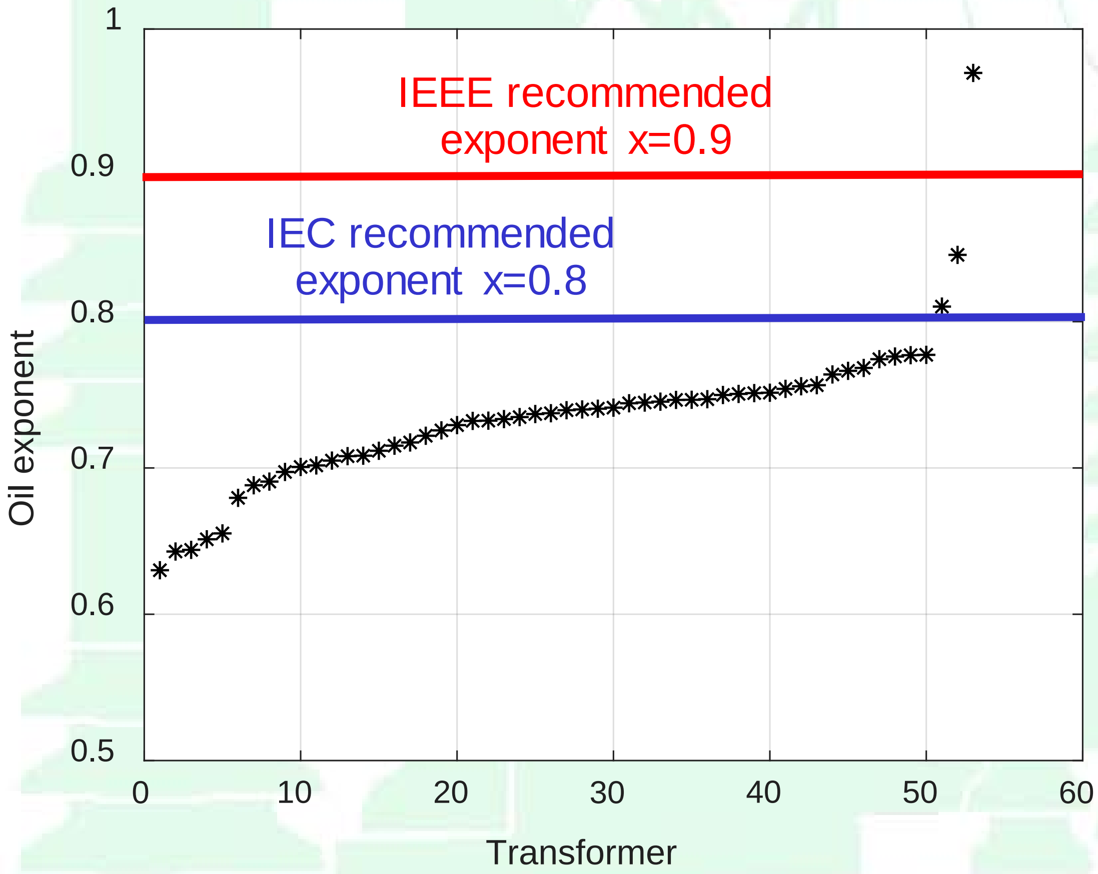
Example with FO measurements

400 MVA 230/120/12.5 kV autotransformer

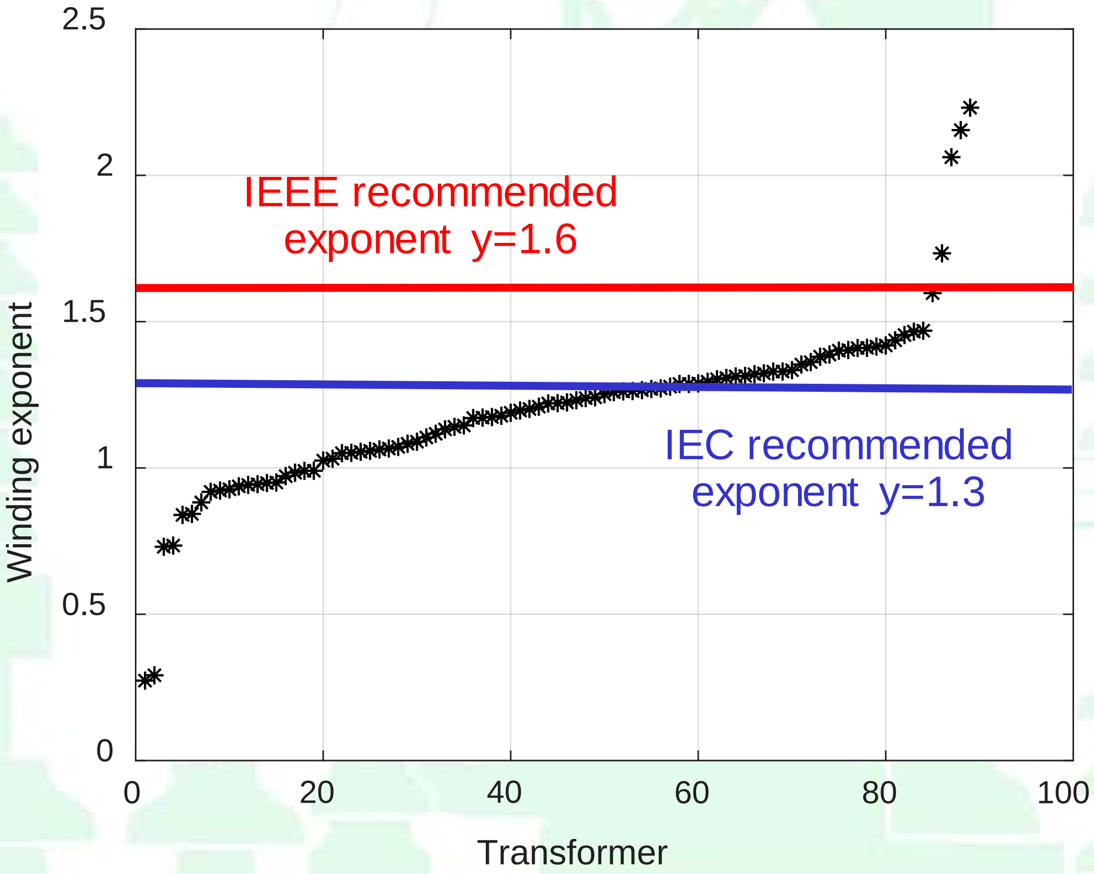


Oil and winding exponent results

Oil exponents (0.75 ±0.05)



Winding exponents (1.20 ±0.29)



Parametric study

Two loading conditions

Short-time emergency: unusually heavy loading of a transient nature (less than 30 min)

Long-term emergency: prolonged outage of some system elements that will not be reconnected before the transformer reaches a new and higher "steady-state" temperature

The LG parameters are **modified individually** and the **loadability variation** (in %) vs. the reference transformer is calculated

Reference transformer
(using IEEE recommended exponents)

x	0.9
y	1.6
$\Delta\theta_{\mathrm{or}}$	45
$\Delta\theta_{\mathrm{hr}}$	35
τ_o	150
τ_w	7
R	8
Cooling	ONAF

Parametric study

Ambient temperature is varied from -30°C to +40°C with 10°C interval

Short-term emergency loading

Pre-event loading is calculated to obtain a hot-spot temperature of 110 deg C

Then, a simulation is performed to determine the maximum loading that can be applied on the transformer until the hot-spot reaches 140 deg C after 30 minutes

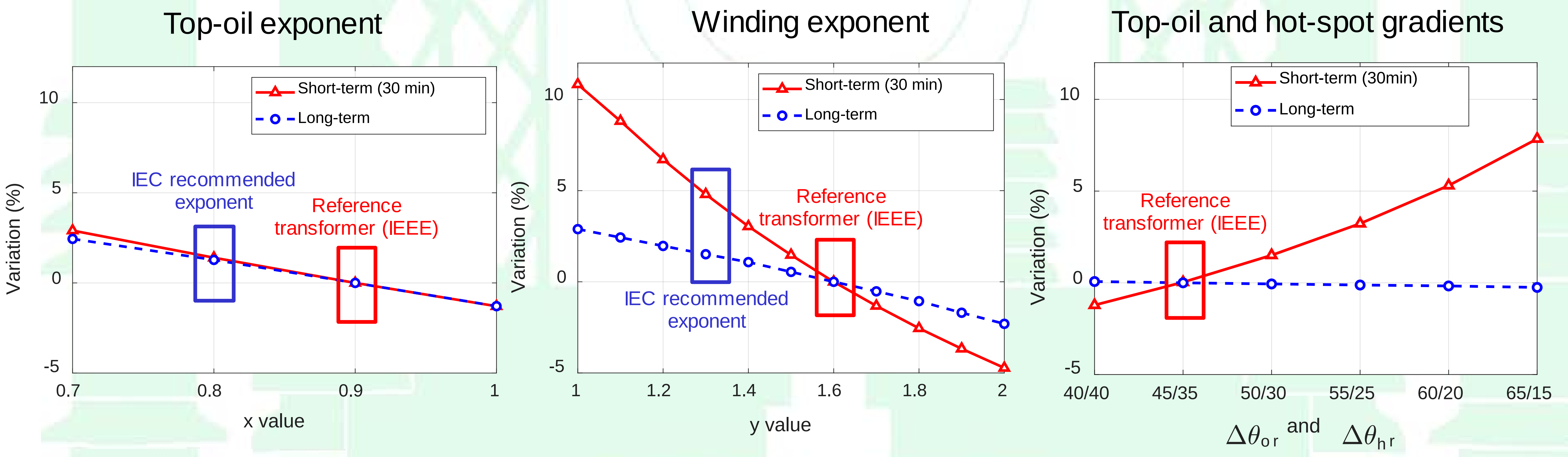
Current is limited to 1.8 pu

Long-term emergency loading

The maximum loading is calculated as if the transformer were operated in steady state at a maximum temperature of 140 deg C

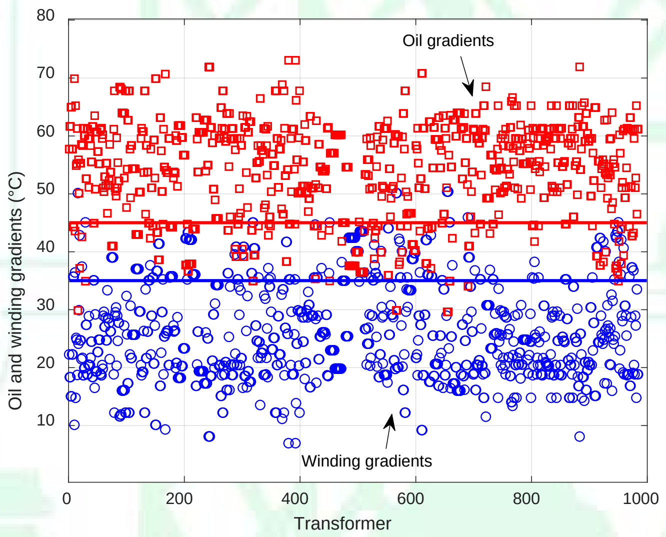
Current is limited to 1.5 pu

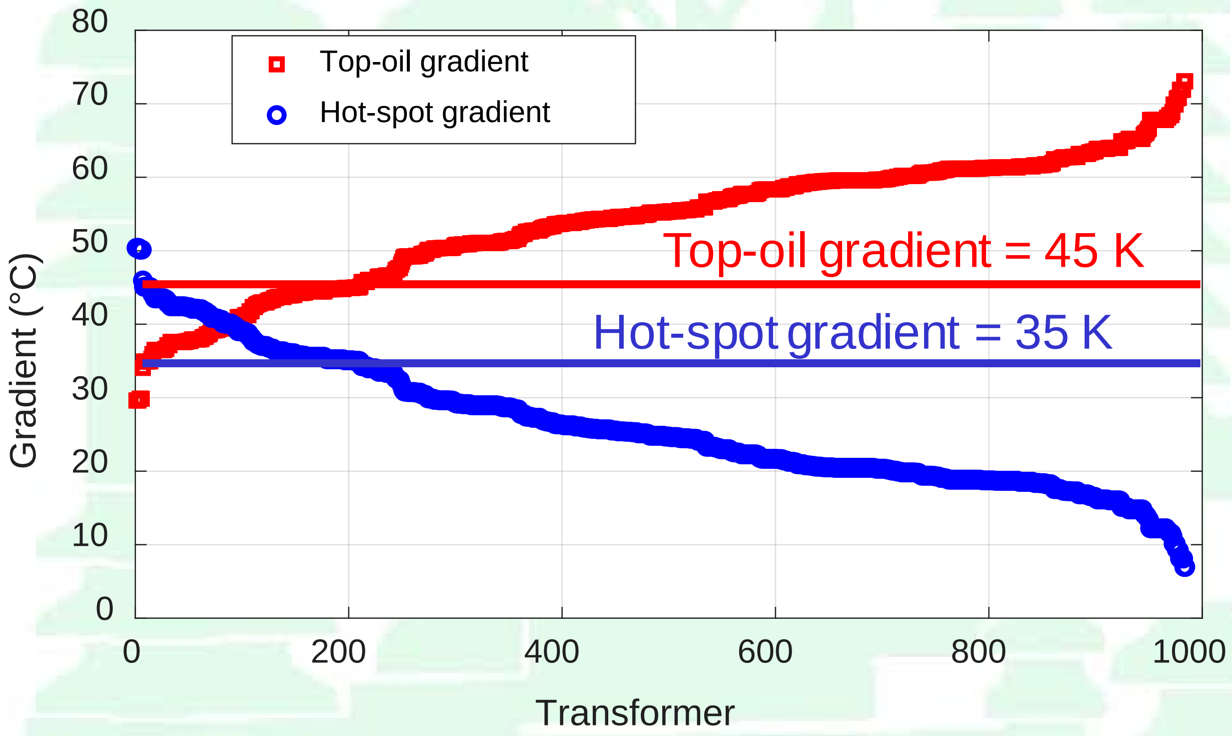
Parametric study results

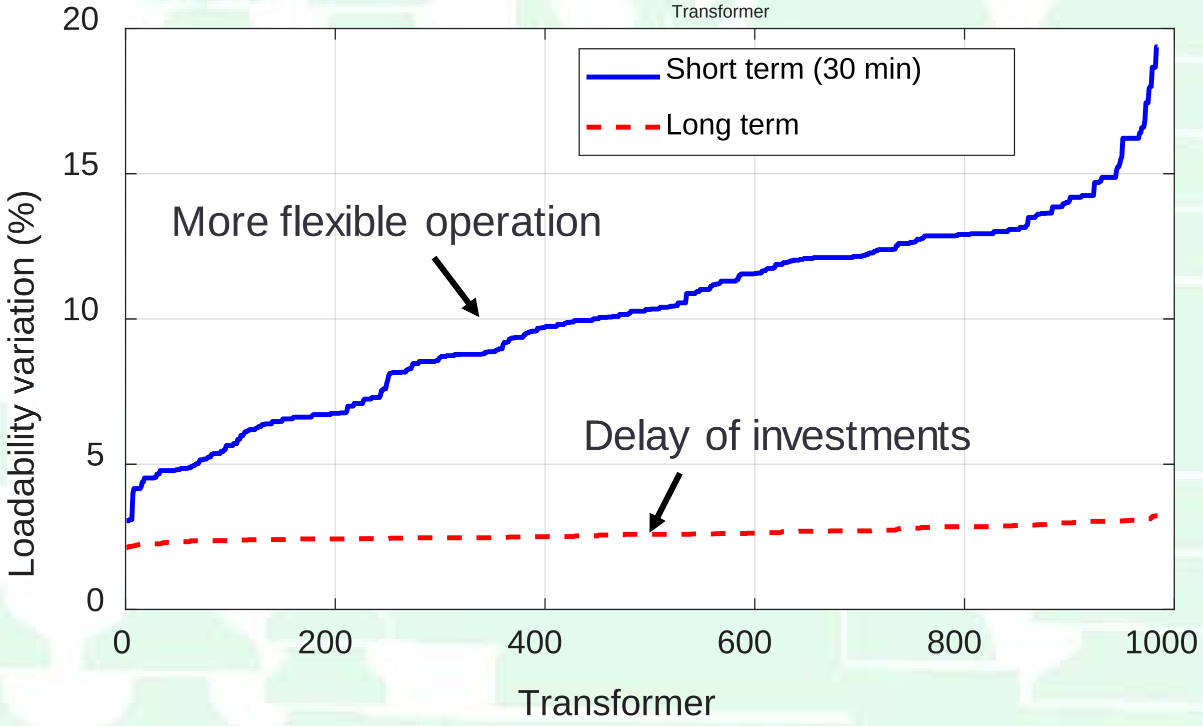


4. PARAMETRIC STUDY OF THE IEC 60076-7 EQUATIONS

Application on a transformer fleet



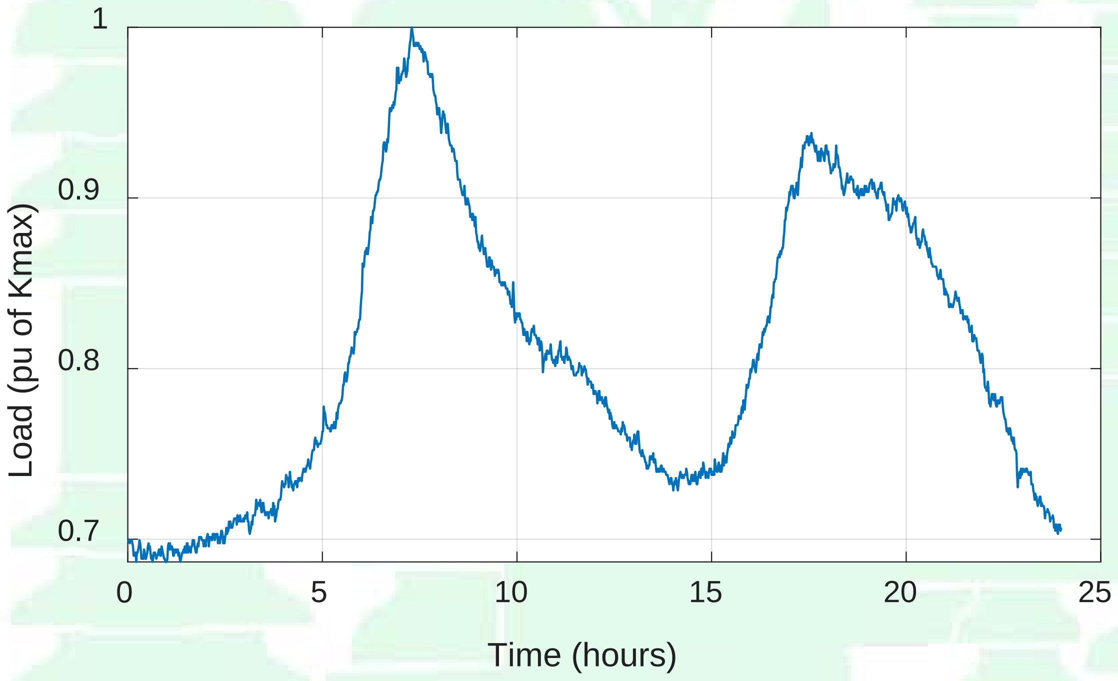


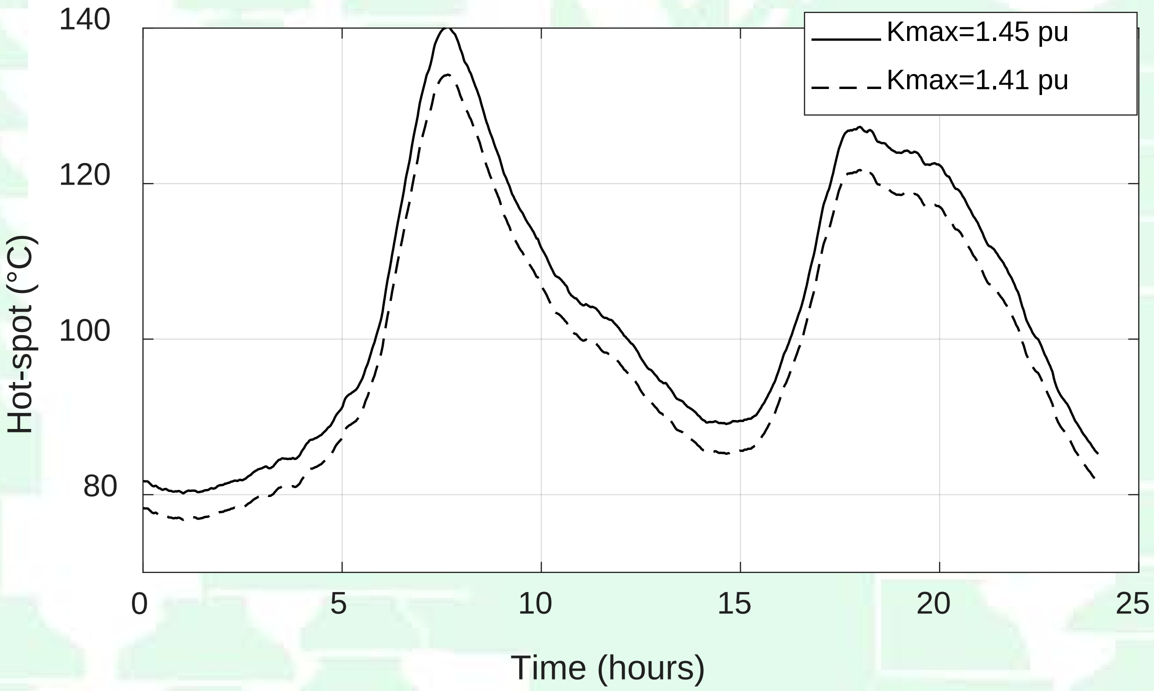


Long-term emergency loading

"Steady-state" is usually not the reality

Ambient temperature 0°C, hot-spot=140°C
1.41 pu in "steady-state"
1.45 pu using real winter load profile (+2.8%)
Taking advantage of the thermal inertia

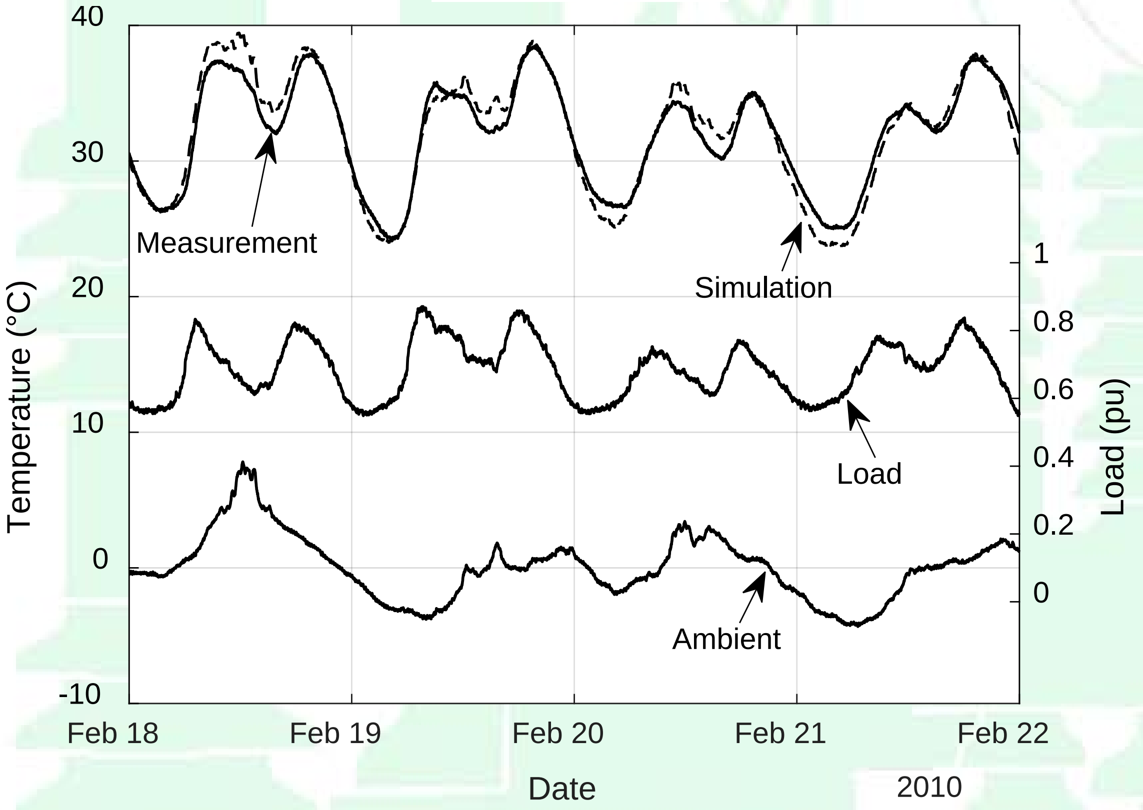


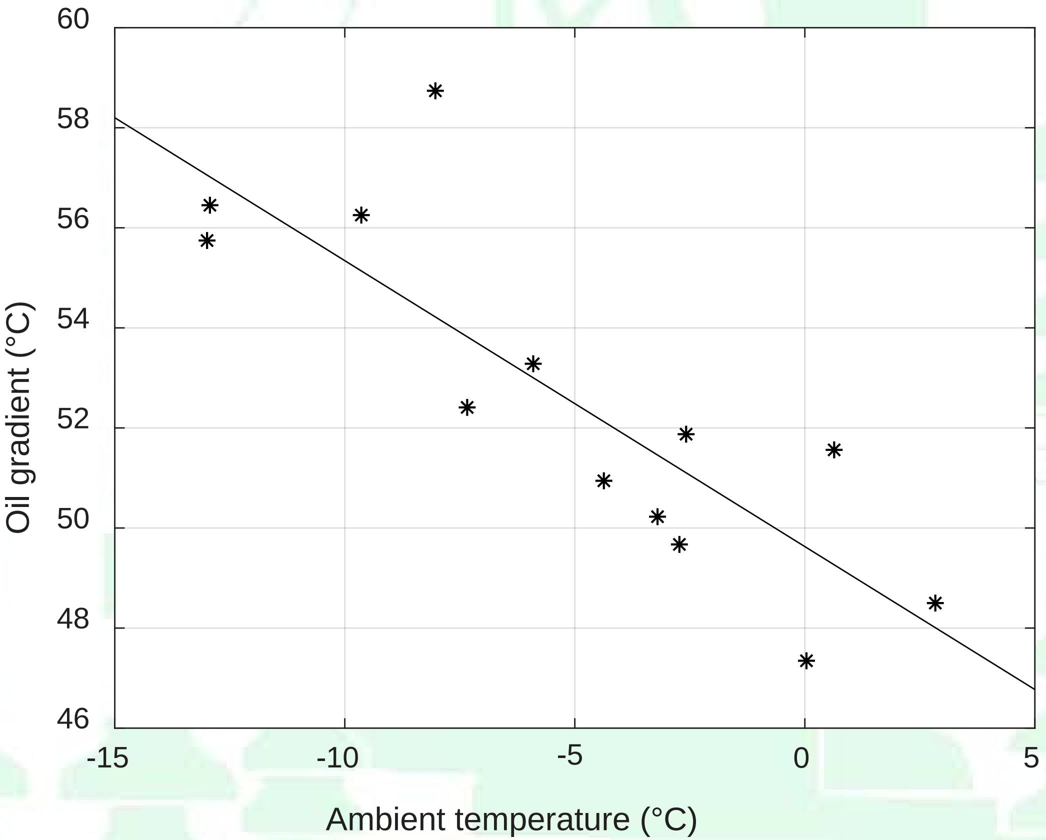


Parameters estimation from field measurement

Data fitting: $\tau_o = 165$ min

$\Delta\theta_{or} = 47.3$ °C, $x = 0.62$





Conclusion

Good transformer temperature **predictions** for short-term and long-term emergency loading scenarios are **essential** for **planning and operation** of electrical networks

This study has shown the importance of selecting **adequate loading guide model parameters** to assess transformer loadability

There would be an interest **for an harmonization** of the international loading guides (IEEE and IEC)

Thank you for your attention

Questions?