The University of Manchester

Evaluation of the Effects on Electrical Losses and Thermal Ageing of Transformer Heat Recovery

28th November 2024

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nationalgrid

Outline

- Introduction
- Development of Transformer Thermal Models
- Effects of Heat Recovery on Electrical Losses and Thermal Ageing
- Effects of Different Heat Recovery Top-oil Temperature Settings
- Conclusions

Introduction

- To achieve net-zero targets, decarbonization of space and hot water heating is essential.

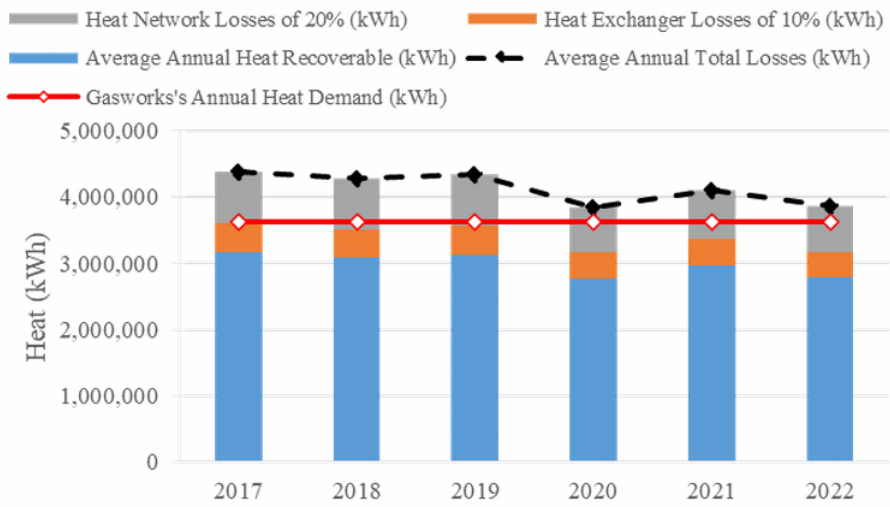
National Grid and SSE to use electricity transformers to heat homes

- When heat demand is close to grid transformers, direct recovery and use of the heat from the transformer becomes an option.

Courtesy of National Grid Electricity Transmission, UK
https://www.theguardian.com/business/2021/aug/24/national-grid-and-sse-to-use-electricity-transformers-to-heat-homesNational Grid and SSE to use electricity transformers to heat homes | Energy industry | The Guardian

Introduction

- A heat exchanger can recover up to 70% of the waste heat from the transformer based on modelling calculations.



- Modelling results show that waste heat could supply around 90% of the site heat demand and a saving of over 60% on costumer energy bills after capex cost.

https://smarter.energynetworks.org/projects/10086459/

Introduction

- Three options of heat recovery systems [1]:
  - (a) heat is transferred to HP (heat pump) when oil pass through an oil-to-refrigerant heat exchanger
  - (b) heat is extracted to the outside via a ventilation shaft
  - (c) heat is transferred to the water-source HP evaporator in the water loop

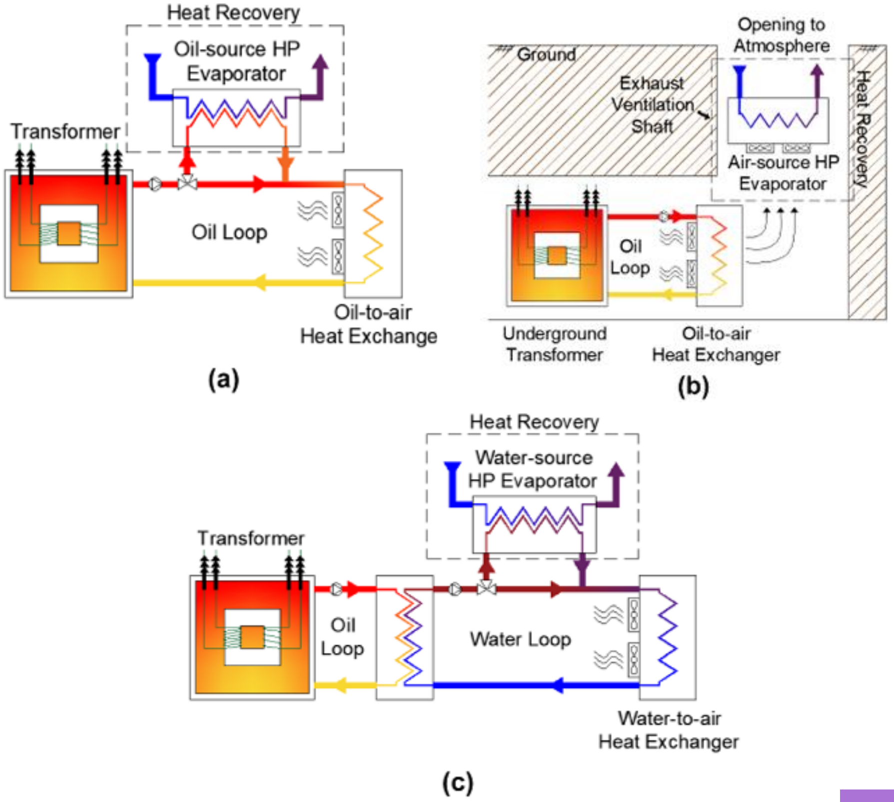


Figure 1: Potential electrical transformer heat recovery options [1]

[1] Roscoe Papini Lagoeiro, H., et al. "Heat Recovery Opportunities from Electrical Substation Transformers." *Energy Reports* 10 (2023): 2931-2943.

Introduction

- The usefulness of the heat depends on the temperature at which it is supplied.

- Higher operating temperature would result in higher aging rate.

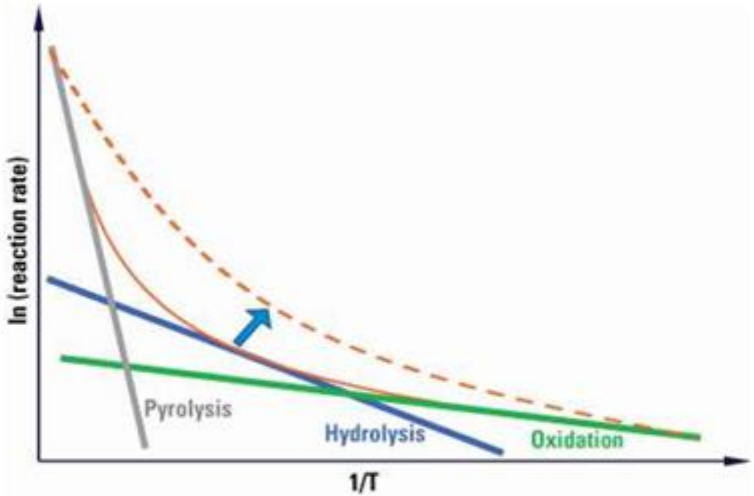


Figure 2: Influence of temperature on aging rate [2]

- The aim of this project is to understand the impact of heat recovery on transformer losses and thermal ageing rate.

[2] Lundgaard, L., et al. "Ageing of liquid impregnated cellulose for power transformers." CIGRE TB 738 (2018).

IEC Thermal Diagram

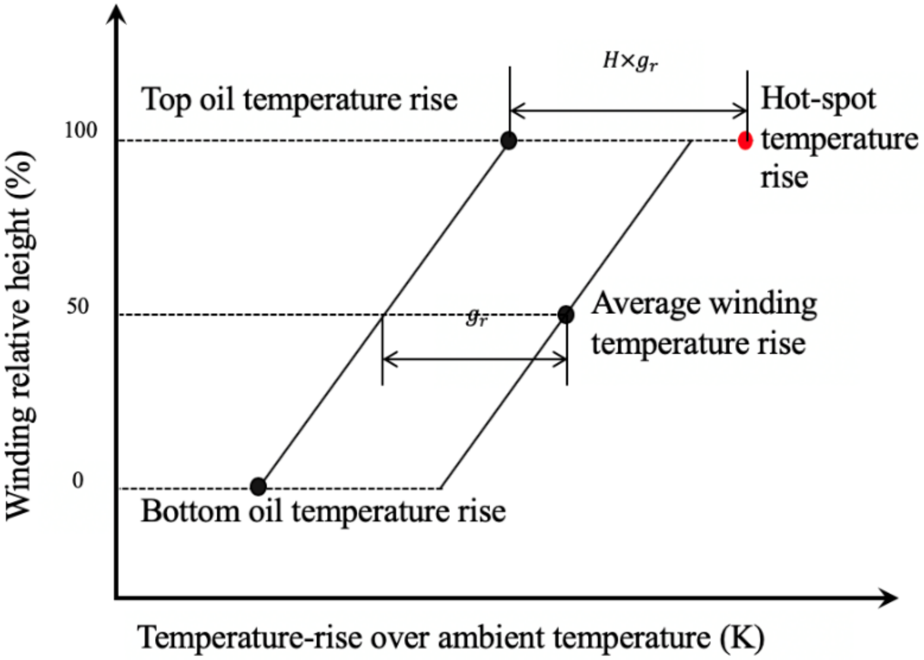
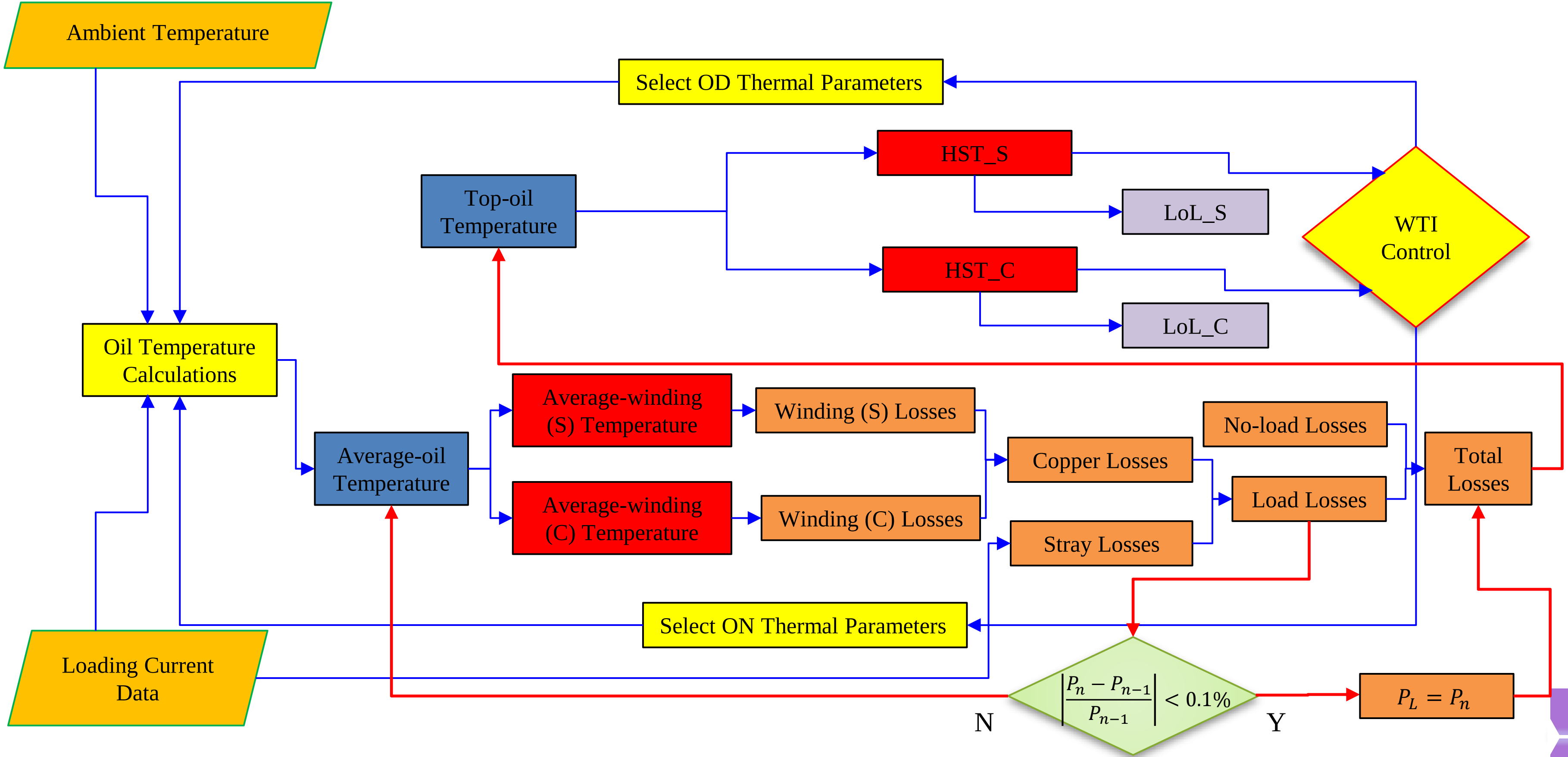


Figure 3: Transformer thermal diagram [3]

- Limitations of IEC thermal model:
  - Unable to provide temperature dependent winding resistance and loss calculations.
  - Does not account for dual cooling mode control by the WTI (winding temperature indicator).

[3] IEC Standard, 60076-7 , Loading guide for oil-immersed power transformers, 2018.

Development of Standard WTI Model



Development of Standard WTI Model

Time constants

- Oil time constant τ_o
- Winding time constant τ_w

INPUT

1. Loading data I
2. Ambient temperature θ_a

Standard WTI Model

OUTPUT

1. Top-oil temperature
2. Ave-oil temperature
3. HST
4. Ave-winding temperature
5. Ave-winding resistance
6. Total losses
7. Cooling mode (ON or OD)
8. Loss of life
9. Expected lifetime

Factory test data

- Rated load loss $P_{L,r}$
- No-load loss P_{NL}
- Gradient g_r
- Rated temperature rise $\Delta\theta_{or}, \Delta\theta_{avor}$ and $\Delta\theta_{hsr}$

Empirical parameters

- Thermal constant k_{11}, k_{21} and k_{22}
- Winding exponent y
- Oil exponent x

Development of Quasi-static Model

Leaving out the oil and winding time constants

- Time constants were not considered in the heat recovery model

INPUT

1. Loading data I
2. Ambient temperature θ_a

Quasi-static WTI Model

OUTPUT

1. Top-oil temperature
2. Ave-oil temperature
3. HST
4. Ave-winding temperature
5. Ave-winding resistance
6. Total losses
7. Cooling mode (ON or OD)
8. Loss of life
9. Expected lifetime

Factory test data

- Rated load loss $P_{L,r}$
- No-load loss P_{NL}
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- Rated temperature rise $\Delta\theta_{or}, \Delta\theta_{avor}$ and $\Delta\theta_{hsr}$

Empirical parameters

- Thermal constant k_{11}, k_{21} and k_{22}
- Winding exponent y
- Oil exponent x

Verification of Quasi-static Model

- To verify this model, a year of representative loading and ambient temperature data from a 400/132 kV, 240 MVA grid transformer was used.

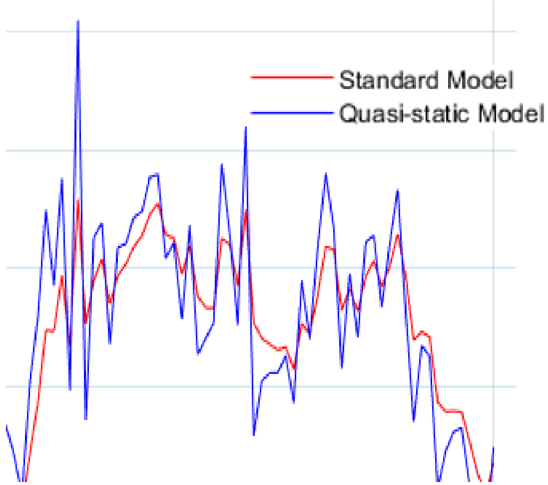

Figure 4: Comparison of HST between standard model and quasi-static model

Table 1: Comparison results between quasi-static model and standard model

	Electrical Losses (MWh per year)	Loss of life (days per year)	Expected lifetime (years)
Quasi-static WTI Model	1363.7	3.94	1899.1
Standard WTI Model	1363.1	3.85	1946.5

- The impacts on electrical losses and loss of life over the whole year are negligible.

Development of Heat Recovery Model

- This system is intended to maintain a **constant** top oil temperature.

- Oil cooling loop
  - Transformer windings
  - Oil pump (**fixed speed**)
  - Oil-to-water heat exchanger

- Water cooling loop
  - Water pump (fixed speed)
  - Heat recovery water-to-water heat exchanger
  - Oil-to-water heat exchanger
  - Dry air cooler (fans & bypass controlled by three-way valve)

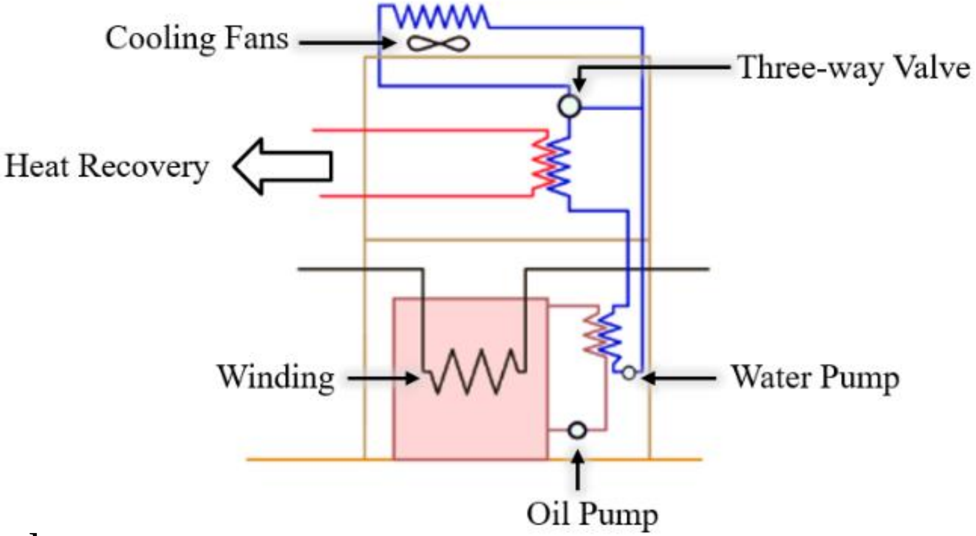

Figure 5: Diagram of heat recovery control scheme

Development of Heat Recovery Model

- Constant Top oil temperature

- Fixed oil mass flow rate (no cooling mode switching, $m_{oil} = m_{rated\_OD}$)

- Temperature difference can be calculated from energy conservation equation:

$$\Rightarrow \Delta T = \frac{P_L + P_{NL}}{m \cdot C_P}$$

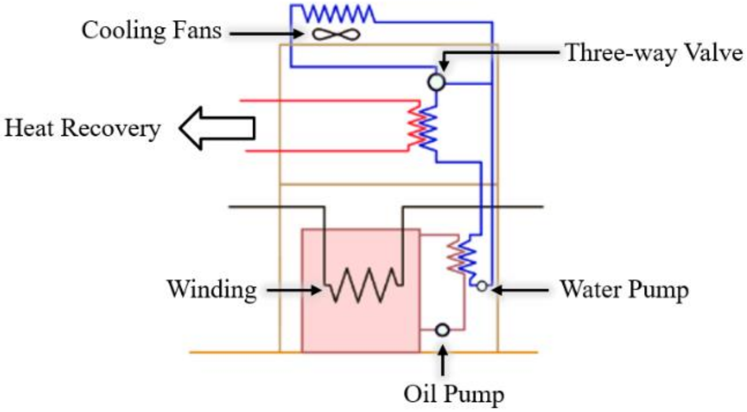

Figure 5: Diagram of heat recovery control scheme

- Average oil temperature can be calculated:

$$\Rightarrow T_{avo} = T_{top}(fixed) - \frac{\Delta T}{2}$$

Comparison of Top Oil Temperatures

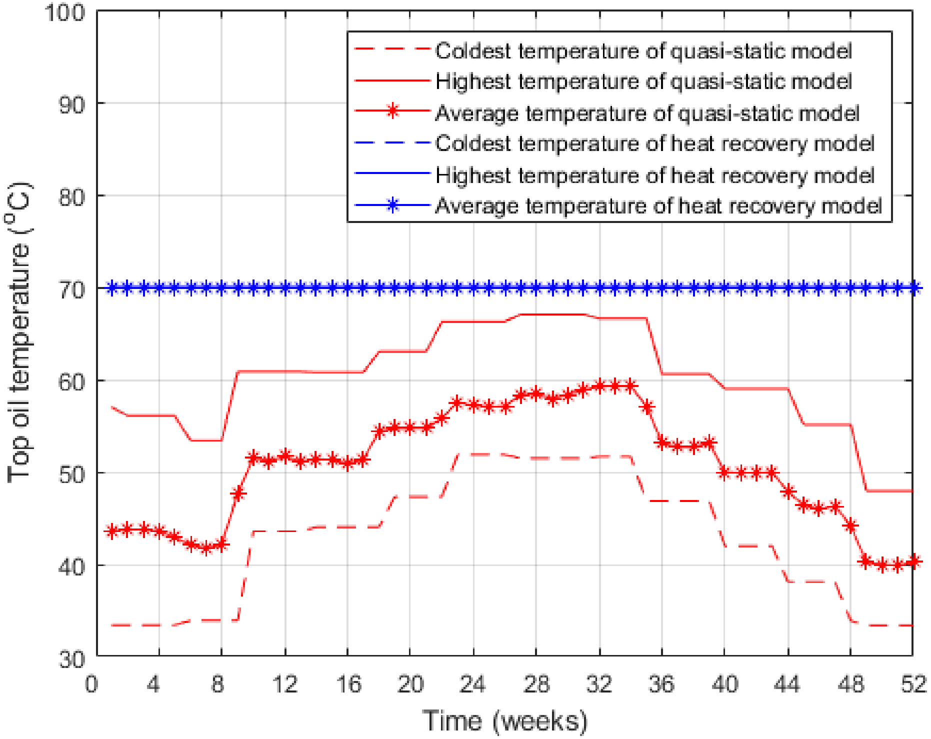

Figure 6: Comparisons of TOT between quasi-static WTI model and heat recovery model over one year period

- Input data from a 400/132 kV, 240 MVA grid transformer (15-minute basis).
- For clarity, the results are shown as weekly maximum, minimum and average numbers.
- Set point for heat recovery model is fixed at 70 °C.

Comparison of Hotspot Temperatures

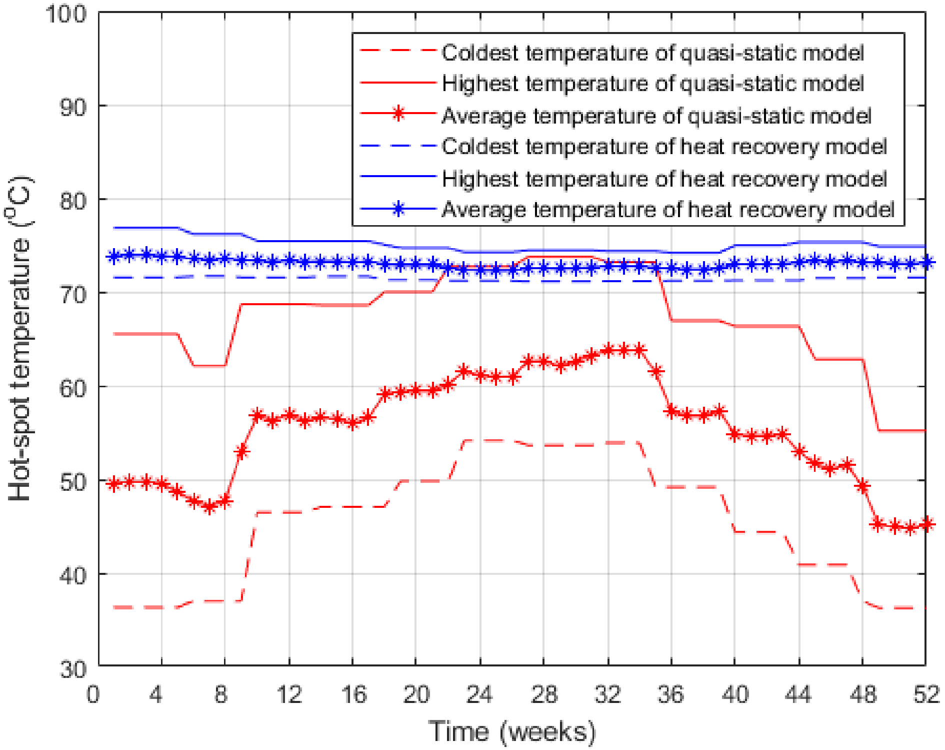

Figure 7: Comparisons of HST between quasi-static WTI model and heat recovery model over one year period

- Due to the higher TOT, the heat recovery model shows a higher hotspot temperature (HST) than the quasi-static WTI model.
- The largest difference occurs in winter.

Comparison of Electrical Losses

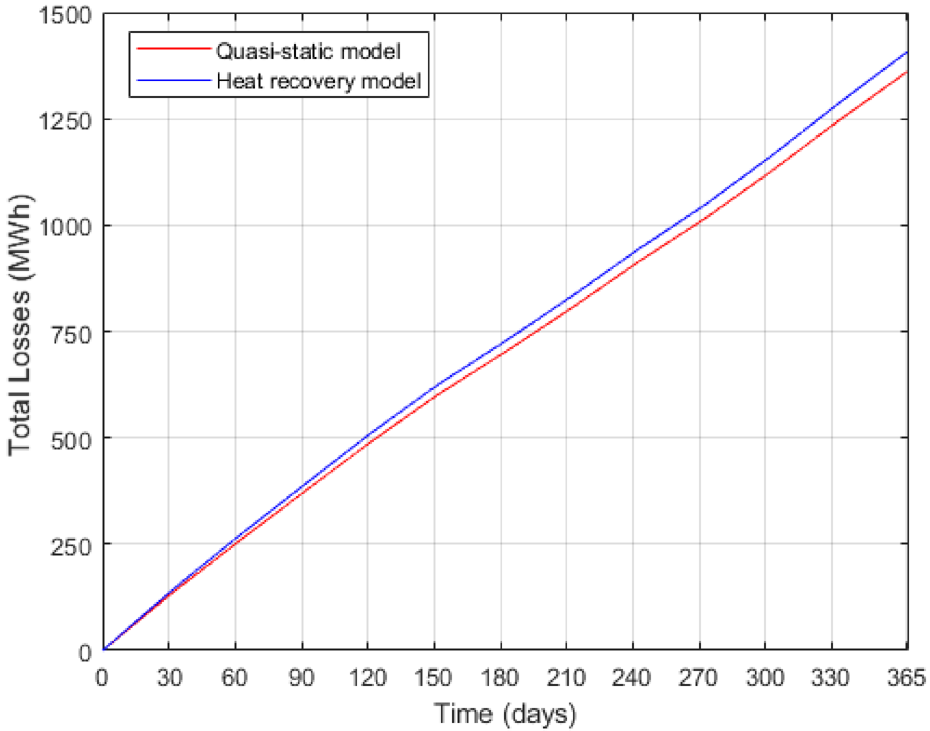

Figure 8: Comparison of accumulated electrical losses between quasi-static WTI model and heat recovery model over a one-year period

- $P_{Quasi-static} = 1363.7\ (\mathrm{MWh})$
- $P_{Heat\ recovery} = 1410.5\ (\mathrm{MWh})$
- The heat recovery model shows slightly higher losses than the quasi-static WTI model.

Comparison of Loss of Life and Expected Lifetime

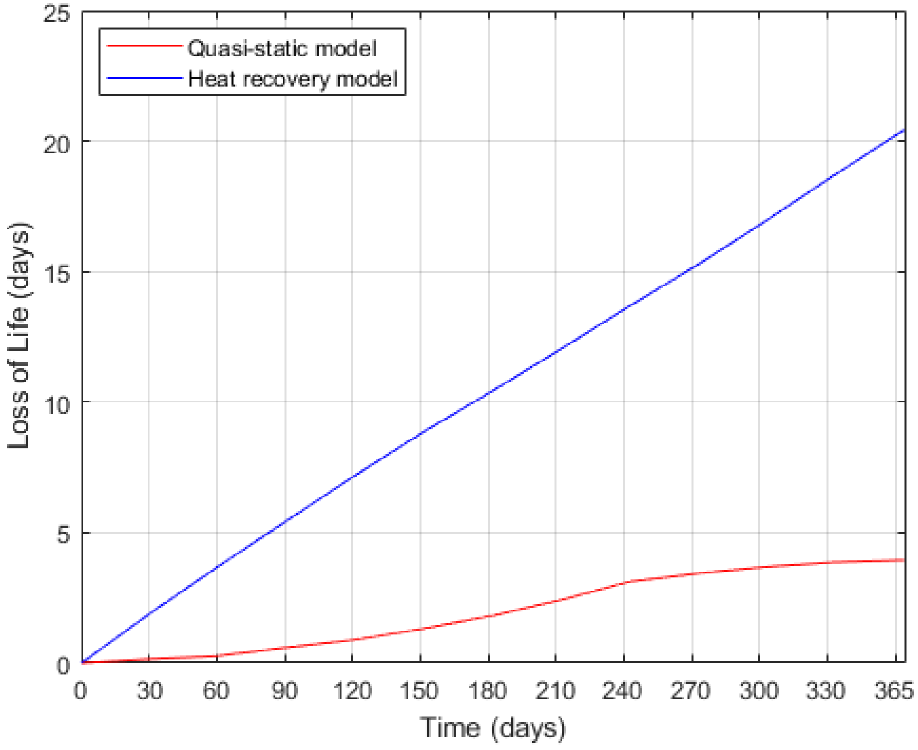

Figure 9: Comparison of Loss of life between quasi-static WTI model and heat recovery model for a one-year period

- Loss of life calculation [3]:

$$L = \int_{t_1}^{t_2} 2^{\frac{\theta_{hs}-98}{6}}\, dt$$

- Total loss of life was represented in cumulative form.

- Expected lifetime for two models:

$$T_{life} = \frac{365}{L} \times 20.5$$

$$T_{life\_Quasi-static} = 1899.1 \text{ years}$$

$$T_{life\_Heat\ recovery} = 366.1 \text{ years}$$

[3] IEC Standard, 60076-7 , Loading guide for oil-immersed power transformers, 2018.

Effect of Different Heat Recovery TOT Settings

		70 °C			60 °C			50 °C	
	Losses (MWh per year)	Loss of Life(days per year)	Expected lifetime (years)	Losses (MWh per year)	Loss of Life(days per year)	Expected lifetime (years)	Losses (MWh per year)	Loss of Life(days per year)	Expected lifetime (years)
Quasi-static Model	1363.7	3.94	1899.1	1363.7	3.94	1899.1	1363.7	3.94	1899.1
Heat recovery model	1410.5 (+3.43%)	20.48	366.1	1390.9 (+1.99%)	6.45	1162.3	1371.3 (+0.06%)	2.03	3689.9

- If the set point temperatures are reduced to 60 °C then the change in losses and lifetime are approximately halved and at 50 °C they become negligible or even represent an improvement over the quasi-static model.

Conclusions

- Transformer thermal models have been developed using MATLAB that can evaluate TOT, HST, average winding temperature and hence derive winding electrical loss and insulation thermal ageing rate, given a loading and ambient temperature profile.

- A comparison between a quasi-static WTI model representing the standard transformer configuration and a heat recovery model representing the operation of a constant temperature heat recovery system, showed that a modest increase in losses and an insignificant reduction in lifetime could be expected for heat recovery with a top oil temperature setting of 70 °C .

- The increase in losses is approximately halved if the top oil temperature setting is reduced to 60 °C and made negligible at a setting of 50 °C.

More detailed information can be found in: Z. Xu, Q. Liu, P. Jarman and G. Wilson "Evaluation of the Effects on Electrical Losses and Thermal Ageing of Transformer Heat Recovery." IEEE International Conference on High Voltage Engineering and Application,, Berlin, Germany, 2024.

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