Final Report

Maximising electric vehicle fast charging by improved thermal management of distribution transformers

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What is RACE for 2030?

Reliable, Affordable Clean Energy for 2030 (RACE for 2030) is an innovative collaborative research centre for energy and carbon transition. We were funded with $68.5 million of Commonwealth funds and commitments of $280 million of cash and in-kind contributions from our partners. Our aim is to deliver $3.8 billion of cumulative energy productivity benefits and 20 megatons of cumulative carbon emission savings by 2030. racefor2030.com.au

Acknowledgement of Country

The authors of this report would like to respectfully acknowledge the Traditional Owners of the ancestral lands throughout Australia and their connection to land, sea and community. We recognise their continuing connection to the land, waters, and culture and pay our respects to them, their cultures and to their Elders past and present.

Disclaimer

Executive Summary

This feasibility study is a precursor to a larger program of future tasks that focus on enabling increased volumes of electric vehicle integration by improving the utilisation of distribution transformers. This Part 1 study demonstrates through modelling, informed by practical heat run tests, the potential to use thermal transformer capacity when considering short duration EV charging profiles that consist of highly peaked loads. It is anticipated that Part 1 is followed by a broader study.

- Part 1 Feasibility: Desktop modelling to confirm and quantify the capacity achievable
- Part 2 Longitudinal study: In-field assessment of two purpose build distribution transformers with thermal sensing using fibre optic probes and data collection deployed in the Essential Energy network

The ultimate outcome of Part 2 of this project is the demonstration and verification of an anticipated increase in transformer capacity by correlating the thermal models with thermal measurements when delivering the peak loads required by fast EV charging. Such evidence will permit more EV chargers to connect to Essential Energy's network, and similarly for other DNSPs whose distribution network characteristics are comparable, before assets are replaced or new assets installed. The business benefit is reduced expenditure on new plant and upgrades. The focus of this report is the potential of improving the thermal modelling and management of transformers thereby improving confidence. The intended benefit is that by better management of transformers Essential Energy and its project partners will defer having to install larger capacity assets, whilst not reducing the operational lifespan of the transformer.

Thermal models for the types of transformers investigated were developed using IEC 60076/7 overload guides and their associated modelling approaches. These approaches define an accumulated life function of the age of the paper within the transformer.

This desktop modelling indicates that even with a high initial 'baseload' utilisation (0.75 p.u. of rated MVA) from existing demand, the transformer has sufficient thermal capacity provided by the oil to handle the additional load from fast charging and the additional load is considerably more than the expected 0.25p.u. This is because the duration of a typical fast-charging session is relatively short compared to the thermal time constant of the oil, resulting in a smaller temperature rise in the transformer oil than would be anticipated under a steady-state thermal model.

The potential of the transformer to deliver additional demand is further increased when considering its emergency loading capability, which allows for rated currents of up to 1.8 p.u. and 2 p.u. for long-time and short-time durations, respectively. However, it should be recognised that this is only feasible if the transformer ancillaries are also capable of the increased currents such as the capacity of the bushings, tap switches, earthing, and other internal components. The long and short-time emergency ratings will potentially have a tremendous positive impact on the capability of transformers to deliver useful and impactful charging capability as electric vehicle usage accelerates. Further still with Essential Energy's typical distribution network characteristics, the additional capacity released will not only provide improved customer experience of fast charging but will also defer considerable potential additional expenditure on network augmentation.

Part 2 of this project includes further research and would explore in more detail the additional transformer capacity and the methods by which it can be utilised. A research scope of work for Part 2 should include the following.

- Establishing two long-term reference sites for the study of EV loads and analyse the difference in thermal performance.
- Assess the heat run tests and their ability to provide useful parameters for online sensing models.
- Perform field tests, capturing the necessary data to assess control options and their performance as well as generating data that can be used to assess the improvements obtained.
- Comparison of ageing trajectories to cost of network augmentation using traditional transformer limits.

- Determine the value of dynamically managing transformer thermal limits to release extra capacity thereby avoiding infrastructure expenditure.
- Impact of utilising additional transformer capacity on auxiliary equipment.
- Quantification of increased power losses from transformer overload in terms of cost.
- Investigate the impact of harmonic currents from DC fast chargers on iron and copper losses, and their impact on transformer thermal performance.
- Using the data from the transformer test sites to improve the thermal model for EV peak loads.
- Research and develop thermal model suitable for distribution transformers and using these models for existing transformers to utilise untapped capacity.
- Consider cyclic rating and emergency rating of 1.5 and 1.8 p.u. and see the impact on loss of life.
- Investigate forced air cooling for leveraging extra capacity.
- Analyse the performance of mineral oil and ester oil in distribution transformers in terms of thermal response to EV peaky loads
- Apply dynamic management of transformer thermal limits to other distribution transformers that are overloaded
- Understand consumer behaviour concerning EV fast chargers and realistic load profiles

In addition to this list are the original driving motivations for the proposal submission to RACE2030 which are in the original submitted proposal.

Transformer Details and Specifics

There are two test locations in Essential Energy's network (Holbrook and Coffs Harbour) that will provide in-field practical temperature measurements, and this study sets out to determine the impact fast charging EVs peaky short duration loads would have on the utilisation of these distribution transformers. Specifically, the number of additional 250 kW EV chargers that can be installed and operated on a 1 MVA transformer, with varying levels of charger utilisation, before the transformer experiences accelerated ageing according to the gain model of the insulating paper. Three EV congestion scenarios- low (15-minute gaps between two consecutive charging sessions), medium (10-minute gaps), and high (5-minute gaps) are investigated. The study revealed that the transformer benefits from its thermal inertia, overnight cooling, and the intermittent nature of EV charging, prevents prolonged overloading.

In all the EV congestion scenarios, it is discovered that, for low utilisation cases of 25% and 50%, the transformer can support up to four 250 kW EV chargers delivering a total of 1977 MWh of annual energy for EV charging without experiencing accelerated ageing. Whilst significant accelerated ageing is expected in a high utilisation case of 75% when adding three or four 250 kW EV chargers on a 1 MVA transformer this work has demonstrated in theory that the addition of two 250kW EV chargers is feasible without accelerating ageing. The additional anticipated load relies on the thermal capacity (thermal inertia) of the oil to absorb the additional losses. This slows the rise of winding temperature hence reduces the accumulated ageing. It was also observed that the hot-spot temperature responds at a much lower rate than the step increase in load current generated by the charger.

Limitations of Part 1 study and the need for Part 2

This report goes some way to demonstrating the additional capacity available. A caveat is that many of the simulated scenarios in this report are specific and numerical hence the outcomes cannot be generalised. The location, the local network and the predicted charging profiles (the charger and the customer requirements) all have an impact on the additional capacity. These numerical methods of determining improvements in particular scenarios provide confidence that significant overloading of the windings can take place.

This report also presents a control strategy to regulate the interaction between the electric vehicle, the charger, and the transformer hotspot temperature. The range of potential instrumentation options are also articulated where each option provides improved control over the hot-spot temperature at the cost of embedding more sensors in the oil tank. These options nevertheless provide an opportunity to consider balance customer expectations of fast charging with operational loading on transformers if the economic benefit of the improved control is positive when accounting for the cost of instrumentation. There is potentially an option of developing a low-cost sensor and the Part 2 study would provide an indication of a specification for such a sensor.

This Part 1 study is based around the IEC and IEEE transformer overload guides and desktop models derived from these standards and EV fast charge load profiles. The authors note the following factors that are relevant to the scope of work for Part 2.

1. Both the IEC and IEEE overload guides were developed for zone substation transformers and the IEC also includes guidance for distribution transformers. These guides have been shown to be reliable and can be further refined using data from heat run tests. Nonetheless, the thermal behaviour of these assets with peaky loads may be significantly different.

2. The possible impact of high-order harmonics from inverters associated with charging has the potential to lead to undesirable transformer heating which may reduce the rating. Whilst each charger must satisfy the relevant standard in terms of power quality and harmonics, the size of the single EV charger load means that load diversity cannot be relied upon to aggregate harmonics. Indeed, three 250kVA chargers on a 1MVA distribution transformer could introduce a cumulative THD well above 5%.

Figure 1. Foil wound diamond dot winding

Figure 2. Circular layer strap windings

3. Oil types. The thermal behaviour of ester-based oils and conventional mineral oils differ substantially. Transformers filled with ester oil can meet the definition in IEC60076/14 of high temperature insulation and run significantly hotter (up to 20 degrees). There is a price premium for specifying ester oils but the impact of the improved thermal performance of ester oils may change purchasing specifications for distribution transformers used in fast EV charging applications. Furthermore, it may be viable to retro fill existing mineral oil transformers with ester oils to achieve higher thermal ratings for brownfield EV fast charger deployments. In Part 2 of this study one transformer will be filled with mineral oil, the other with esters presenting a comparison basis.

4. Thermal models are conservative, and desktop models must be calibrated against real world experience [4]-[6]. Part 2 of this study enables calibration of the specialised transformers and their model parameters and possible alternative overload models for peaky short duration loads.
5. Transformer design parameters: Aside from differentiating between rectangular wound and circular wound transformers there are other factors that affect thermal behaviour including the ratio of core and coil volumes against oil volumes and cooling methods employed in the transformer design. Whilst distribution transformers rely on natural convection and are primarily ONAN, the design and efficiency of the cooling arrangement affects the calculated thermal hot spot versus the actual hot spot. The specialised transformers used in Part 2 will be able to practically examine this with repetitive peaky loads.
6. For Part 2 the parameters of the thermal model of the transformers will be known as the transformers have undergone heat run tests. This test data from Part 2 provides critical transformer behavioural insights and parameters for thermal modelling.
7. Aged assets in service do not perform like new assets. As oil ages in the presence of oxygen it oxidises and creates acidity. For assets free breathing, moisture content can be an issue. Both acidity and moisture have an impact on paper ageing and overload of assets with compromised oils can rapidly accelerate ageing. Part 2 of this study will examine factors to apply to service aged assets though it is noted that oil off-take for testing could be problematical.

Therefore, there is a huge potential for transformer loading to improve both the customer experience and the operation and utilisation of the existing network. This report outlines the potential of the Part 2 study with options such as applying modern control techniques, data analytics, machine learning and possibly artificial intelligence techniques. Part 2 may identify a wholesale increase in the opportunity for existing networks to deliver customer expectations of fast charging and avoid or defer network investment.

Contents

Introduction

DC fast charging of electric vehicles (EVs) presents a challenge for distribution companies, as proponents installing chargers must fund infrastructure upgrades when capacity is insufficient, creating a significant upfront barrier. Adopting flexible rating regimes could mitigate customer costs and accelerate charger deployment. Alternatively, there is the potential to explore untapped existing capacity that could delay the need for such investments. This report focuses on the latter, providing a detailed analysis of the impact of DC fast charging on transformer thermal performance and ageing, based on representative EV charging profiles, reflective of commonly available EVs in Australia.

A transformer thermal model based on the IEC 60076-7 standard was applied and fitted to analyse the effects of EV peak loads at a fine-granularity level. This model examines the impact of short-term power surges that occur when EVs are charged at their acceptance rates, which can reach up to 270 kW—a substantial rapid demand for a 1 MVA distribution transformer load. Using the model, the effect of EV charging patterns, including inter-session rest periods, using charging profiles of 23 EVs, is analysed focusing on transformer ageing and temperature rise. Additionally, the study examines how variations in non-EV load influence the transformer's performance when also supplying peak EV loads.

A control strategy is proposed and implemented on the developed transformer thermal model, considering both EV peaky loads and non-EV load. By taking advantage of favourable ambient temperatures and extended operation below the nameplate rating, the control strategy enables the dispatch of additional capacity for EV peak loads without compromising the transformer's lifespan or its scheduled retirement. Figure 3 presents the research methodology employed to assess the feasibility of distribution transformers supporting EV chargers without requiring upgrades.

Background

The Australian Government aims to accelerate electric vehicle (EV) uptake through various initiatives, including a partnership with NRMA as part of the Driving the Nation fund [1]. A key aspect of this effort is the allocation of $39.3 million to build 117 fast EV charging sites, to ensure that fast chargers will be available approximately every 150 km along national highways. To facilitate the uptake of EVs, the Australian Government derived Australia's first National Electric Vehicle Strategy in 2023 to accelerate the adoption of EVs [2]. By 2023, over 180,000 EVs were on Australian roads, doubling each year since 2020. The Electric Vehicle Council anticipates that, with ongoing policy backing, the market could maintain an annual growth rate of 30-50% [3].

To maintain the growth of EVs to support the Australia's climate targets, the associated fast charging infrastructure will play a key role. The charging patterns of EVs, controlled by their battery management systems, combined with the thermal inertia of transformers, create an opportunity to utilise the untapped capacity of transformers powering fast-charging stations. Utilising this capacity beyond the nameplate rating could help prevent expensive infrastructure upgrades, thereby lowering costs for distribution companies. Overload guides such as IEEE C57.91 and IEC 60076-7 exist that can be used as a reference in estimating loss of life when operating the transformer beyond nameplate capacity.

To unlock the untapped potential of transformers, it is essential to examine the impact of EV charging sessions on transformer thermal performance. This research aims to investigate the impact of EV charging on transformer thermal performance and provide recommendations for electricity distributers to navigate the challenges arising from huge uptake of EVs. A thermal model based on IEC 60076-7 is created in MATLAB for analysing transformer behaviour under EV loads at a granular level, such as less than a minute. This approach enables an in-depth study of transformer thermal behaviour, considering that winding time constants, typically ranging from 3 to 5 minutes, influence hotspot temperature rise. The differentiation in time constants is influenced by the materials used in the windings, such as copper CTC or strap for power transformers and aluminium foil for distribution transformers. Simulations are conducted considering a 1 MVA transformer, using representative charging profiles of EVs commonly used in Australia.

The goal for the project is to improve asset utilisation for use with EV charging. Distributors have to make every dollar count, and so the aim of this study is to provide distributors with the understanding of how EV chargers will impact transformers, so EE can make the best asset management decisions into the future. Essential Energy would be first utility to include this data on the utilisation map enabling proponents to pick sensible locations. The modelling in this report could be used to inform the adaptation of the utilisation map which itself is a useful outcome.

1) A key parameter is to understand the loading of a transformer with EV chargers attached. It is imperative that distributors be aware of the impact on their assets. In particular, the life and operating temperature is important, because it drives investment which could be unnecessary.

2) The research methodology was therefore to:

  a) Investigate different EV charger technology.

  b) Consider consumer charging behaviour.

  c) Look at EV charging demands.

  d) Model the impact of various consumer behaviours and charging technology on the operating temperature and life of a transformer.

  e) Evaluate impacts on the distributor's transformer asset base.

  f) Propose any changes to asset management methods.

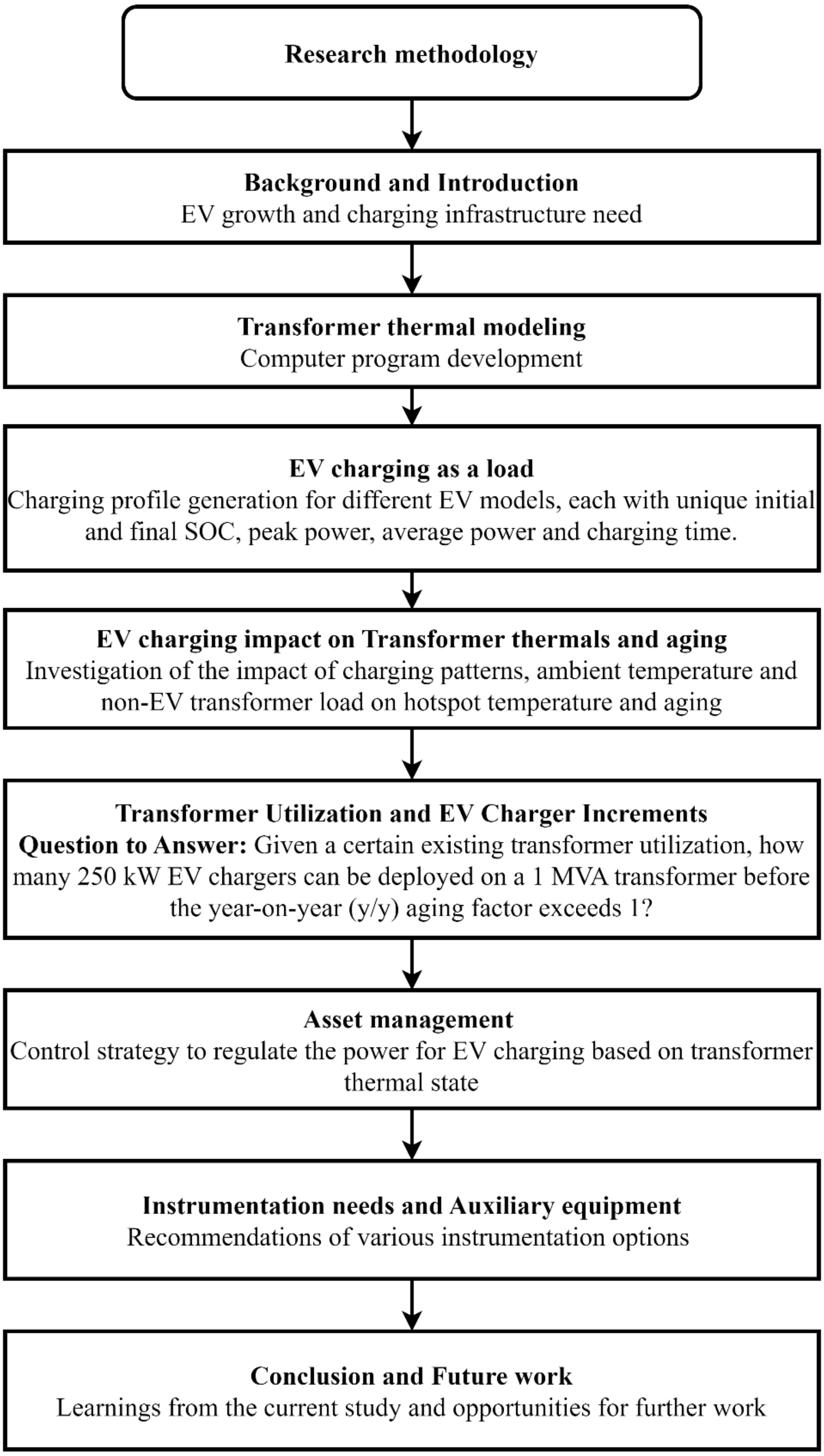

Figure 3. Research methodology employed to assess the feasibility of distribution transformers supporting EV chargers without requiring upgrades.

Transformer thermal modelling

Two commonly used methods for modelling transformer thermal behaviour are provided in IEEE C57.91 and IEC 60076-7. IEEE C57.91 suggests averaging ambient temperature over a 24-hour period to determine hotspot temperature. The differential equation-based thermal model in IEC 60076-7 accounts for time-varying load factor (K) and ambient temperature, which is critical for power dispatch to EVs based on transformer thermal state. To ensure accurate hotspot and top-oil temperature estimation, the time step must be less than half of the smallest time constant. Thermal constants are calculated from transformer heat run tests.

This study adopts the IEC 60076-7 model, as it supports fine granular analysis of loads, which makes it suitable for use with EV peak loads. Note that IEC60076/7 doesn't consider harmonics. Moreover, in Australia, transformer overloading guideline are set by AS/NZS 60076-7, that is based on the IEC 60076-7 loading guide. Tyree Transformers has used these guides for the two transformers they have manufactured with specialised instrumentation for this project to be deployed in Part 2 of the project.

Figure 4 illustrates the thermal model of a transformer presented in IEC 60076-7.

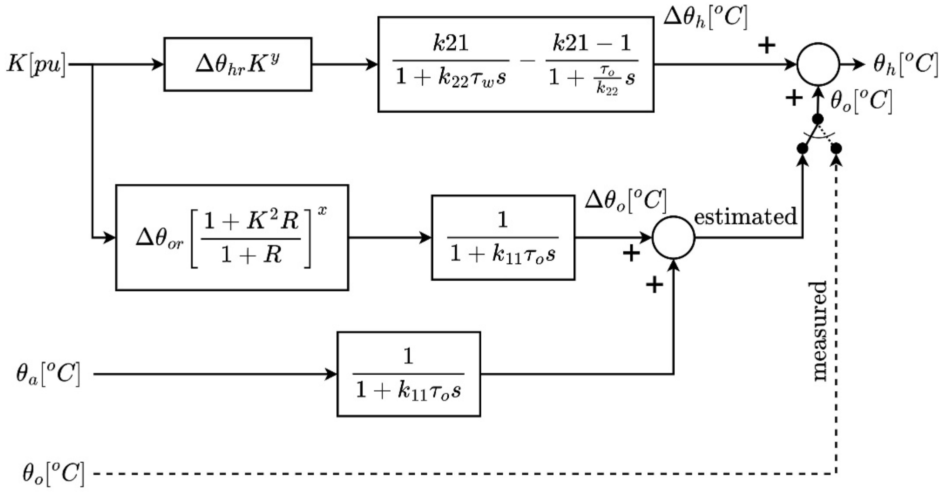

Figure 4. Block diagram of the thermal model of a transformer provided in IEC 60076-7.

Referring to Figure 4, the second block in the topmost path depicts the dynamics of hotspot temperature rise. The first term, with the numerator k21, represents the hotspot temperature rise corresponding to the load factor K, prior to considering the effects of changing oil flow around the hotspot. The second term, with the numerator k21–1, accounts for the slower variations in oil flow past the hotspot. Together, these terms capture the phenomenon where a sudden increase in load current can lead to an unexpectedly high peak in hotspot temperature shortly after the load change. EVs can demand extremely high currents for short periods when charging at their maximum acceptance rates, such as the Tesla Model Y at 250 kW, Audi e-tron GT at 270 kW, and Hyundai Ioniq 5 at 350 kW, which can impose a significant step load increase on a 1 MVA transformer. The IEC 60076-7 model, therefore, can study the impact of these EV loads on transformer performance. Additionally, it provides more precise definitions for nominal, short, and emergency cycling, which can be applied in this analysis. If the top-oil temperature is measured as an electrical signal, an alternative approach can be used by selecting the dashed line path in Figure 4. In this case, the top-oil calculation path is no longer needed. Table 1 lists the parameters utilised in the model for mineral oil, as specified in the IEC 60076-7 loading guide. It is important to note that these parameters may vary between transformers and need to be adjusted using data from heat run tests, for the Essential Energy's special-purpose transformers in Part 2 of the study.

Another aspect to consider is excessive gas generation in the transformers for Part 2. Based on a past study for distribution transformers with high gas levels pressurising the lid were found with fluctuating or unbalanced loads causing internal gas generation with particular gases of Hydrogen and Acetylene. Whilst there were no reported problems with the transformers this may be something to be considered in Part 2 including current harmonic.

To evaluate the thermal performance of transformers under EV peaky loads and determine the potential for dispatching additional capacity, the IEC 60076-7 thermal model is utilised. Figure 5 details the flowchart of the MATLAB-based computer program developed for this project. This flowchart implements the IEC 60076-7 thermal model to support the analysis of the impact of fast charging and the various options available through control schemes developed. The numerical model takes time-series data of load factor (K) and ambient temperature (θ_a) as inputs and provides outputs such as hotspot temperature (θ_h) and top-oil temperature (θ_o), ageing factor, additional capacity, and loss of life.

It should be noted that for various case studies, the program is modified to accommodate specific scenarios, such as adding or removing variables. However, the core structure and flow of the program remain consistent with the flowchart shown in Figure 5. At its core, the code is the IEC 60076-7 thermal model. The remnant capacity is first identified based on regulating unity ageing, followed by an analysis of the effects of EV charging under different conditions, including non-EV load levels, ambient temperatures, EV station congestion, and the gap between EV charging sessions.

Table 1. Thermal parameters of distribution transformer (ONAN) as provided in IEC 60076-7 loading guide.

Parameter	Symbol	Value (unit)
Hot-spot-to-top-oil gradient at $I_{p.u.}$ = 1	$\Delta\theta_{hR}$	23 (°C)
Top-oil temperature rise over ambient in steady state at $I_{p.u.}$ = 1	$\Delta\theta_{oR}$	55 (°C)
Winding time constant	τ_w	4 (min), 240 (s)
Oil time constant	τo	180 (min), 10800 (s)
Ratio of load losses to no-load losses at $I_{p.u.}$ = 1	R	5.0
Thermal model constant	k_{11}	1.0
Thermal model constant	k_{21}	1.0
Thermal model constant	k_{22}	2.0
Exponential power of total losses affecting top-oil temperature rise	x	0.8
Exponential power of current affecting hot-spot temperature rise	y	1.6

Table 2 presents the current and temperature limits for operating Essential Energy distribution transformers beyond their nameplate rating. In normal cyclic loading, higher ambient temperatures or higher-than-rated load currents are applied during part of the cycle, but in terms of relative thermal ageing rate, this is equivalent to the rated load at normal ambient temperature, as lower ambient temperatures or lower load currents during the rest of the cycle offset the increased ageing. Long-term emergency loading involves prolonged overloading leading to higher steady state temperatures, while short-term emergency loading refers to transient heavy loads under 30 minutes, that significantly disrupt normal system conditions. EV peaky loads can utilise the overload allowances in normal cyclic loading, leveraging periods of low utilisation to balance the impact of higher temperatures on insulation lifespan and maintain the transformer's overall ageing within acceptable limits. This leaves short term emergency cycling as an option for asset managers to leverage for further gains in capacity at the expense of asset life. This may present an attractive proposition for in service asset that have had historically low utilisation and commensurate low residual asset value.

Table 2. Current and temperature limits for loading Essential Energy distribution transformers beyond nameplate rating.

Parameter	Normal cyclic loading	Long-time emergency cyclic loading	Short-time emergency loading
Current (p.u.)	1.5	1.8	2.0
hot-spot temperature (°C)	140	160	No limit because it is impractical to control the duration in this case
Top-oil temperature (°C)	105	115	No limit because it is impractical to control the duration in this case

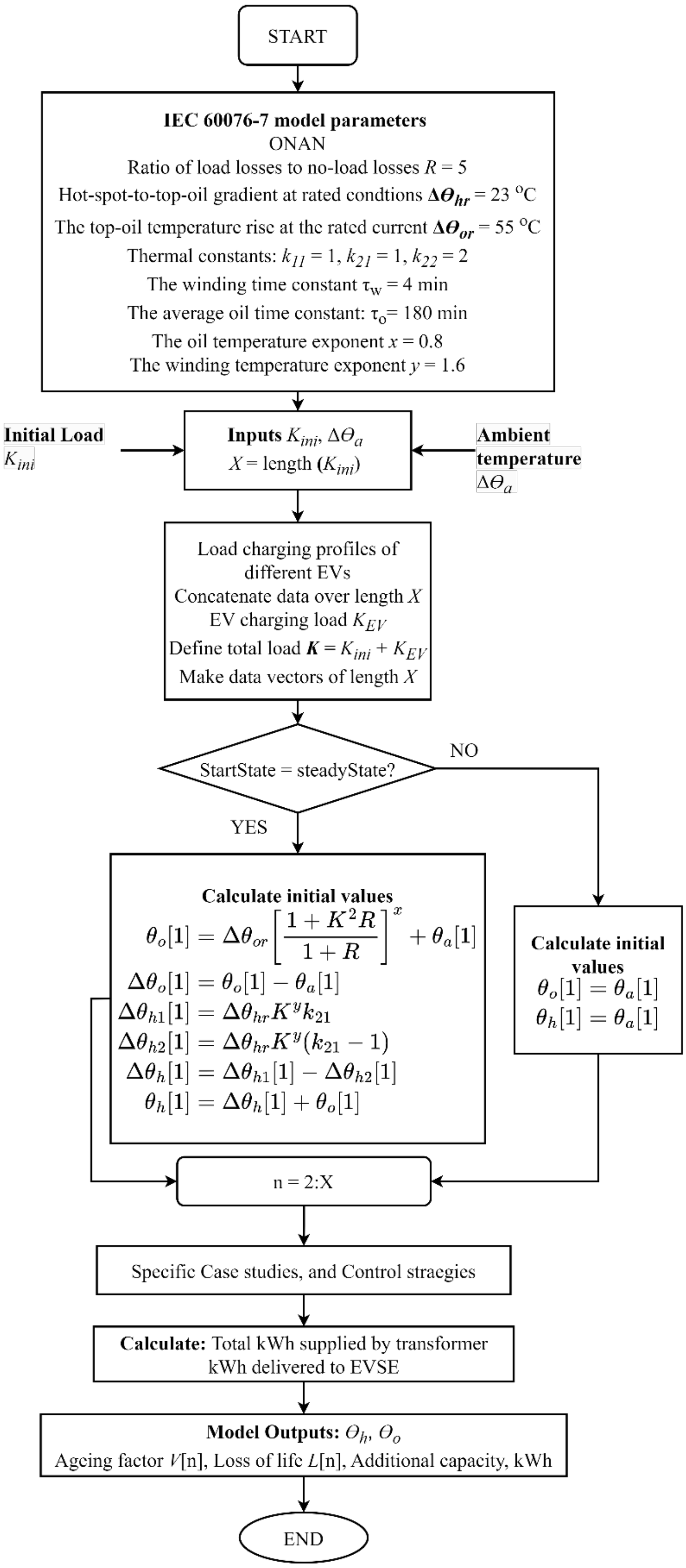

Figure 5. Flowchart of the code developed around the thermal model described in IEC 60076-7. The code provides a suitable interface for users to set a range of model parameters and environmental variables. MATLAB code was utilised.

Case studies using EV short duration peaky loads demonstrating hotspot temperature dependencies

To assess the impact of EV charging on transformer thermal performance, it is important to use EV charging profiles that reflect the charging behaviour of vehicles currently on Australia's roads or expected in near future. This study uses representative EV charging profiles from four vehicles: the Hyundai IONIQ 5, Audi E-Tron GT, Tesla Model 3 Long Range, and Tesla Model S, generated by using Fastned charging curves as a reference.

Figure 6 illustrates the example representative profiles of various EV models which are used to assess the impact of peak charging loads on transformer thermal performance. The charging session profile for the Hyundai IONIQ 5 assumes the vehicle is charged from 9% to 90% SOC, delivering 62.4 kWh in 21 minutes. The charging power reaches a peak of 235 kW, with an average power of 177 kW for the charging session. The charging profile for the Tesla Model 3 involves charging from 10% to 80% SOC, with a peak power of 190 kW and an average power of 147 kW over a duration of 21.4 minutes. For the Tesla Model S, the charging profile includes charging from 5% to 95% SOC, with an average power of 120 kW over a duration of 45 minutes and a peak power of 218 kW.

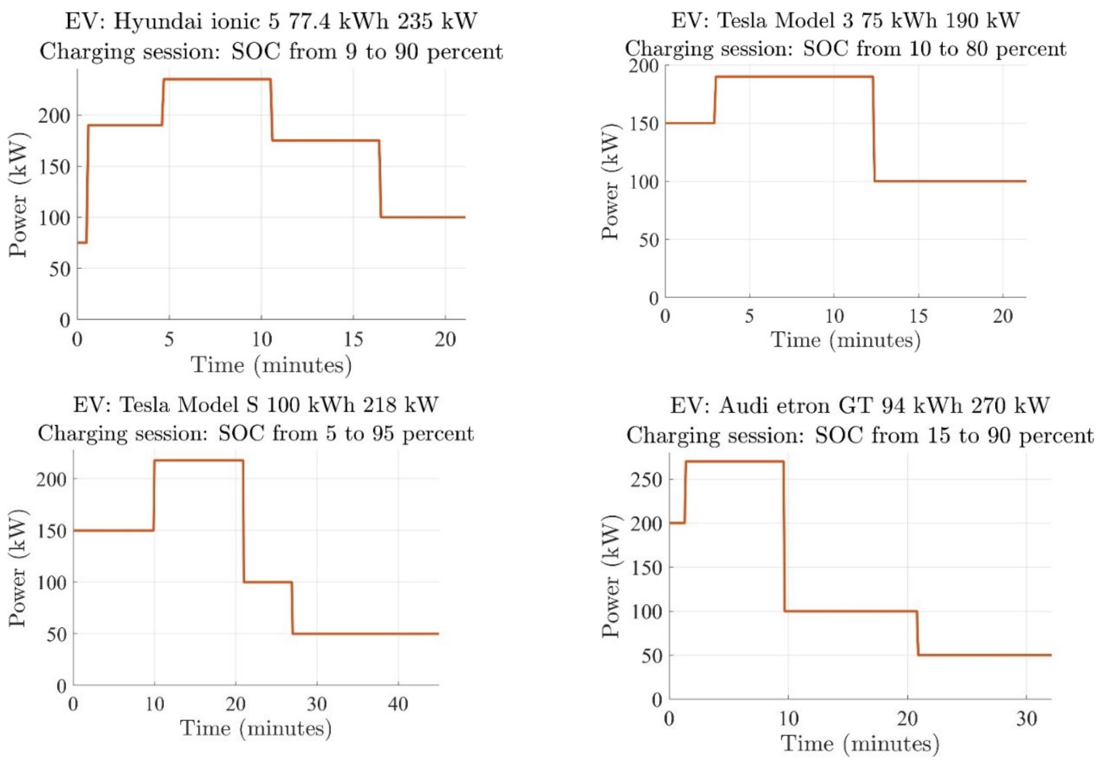

Figure 6. Representative charging profiles of various EVs used in the study, with power averaged over different intervals to simplify simulation. Source: https://www.fastnedcharging.com/en

Table 3 provides the characteristics of the generated charging profiles for various EV models, For the Audi E-Tron GT, the charging profile involves charging from 15% to 90% SOC, with a maximum power of 270 kW and a total energy of 70.5 kWh over 32 minutes. The average power delivered during this session is 132 kW. A short and high average power charging session profile is generated for Audi E-Tron GT from 15% to 65% SOC, delivering 47 kWh in 12 minutes with a peak power of 270 kW and an average power of 226 kW.

Table 3. The generated charging profile characteristics for various EV models used to assess the impact of EV peaky loads on transformer thermal performance.

EV model	SOCini	SOCfinal	Max. charging power	Total energy delivered	Charging session duration
Hyundai IONIQ 5	9%	90%	235 kW	62.4 kWh	21 min
Tesla Model 3	10%	80%	190 kW	52.5 kWh	21 min
Tesla Model S	5%	95%	218 kW	90 kWh	45 min
Audi E-Tron GT	15%	90%	270 kW	70.5 kWh	32 min
Audi E-Tron GT	15%	65%	270 kW	47 kWh	12 min

The charging curves of Figure 6, also defined by the characteristics in Table 3, are sequentially stacked for the study period from 7 AM to 5 PM, as illustrated in Figure 7. Short and high-power charging profile of Audi E-Tron GT, from 15% to 65% SOC, is clustered into four consecutive sessions to simulate aggressive scenarios where EVs, under optimal conditions of state of charge (SOC), state of health (SOH), and battery temperature, charge rapidly for brief durations. The charge curves are derived based on assumed start and end values of the SOC for EVs arriving at charging stations, accounting for varying charging rates. These curves are specific to certain temperature and SOC limits, and they can vary significantly due to factors such as SOC, SOH, battery temperature, and ambient conditions. The fixed charging pattern of Figure 7 is used in this study to simulate the daily charging load. Figure 7 shows that EVs can charge at rates above 200 kW, however, this peak is brief, leading to a lower temperature rise in the transformer as might be expected.

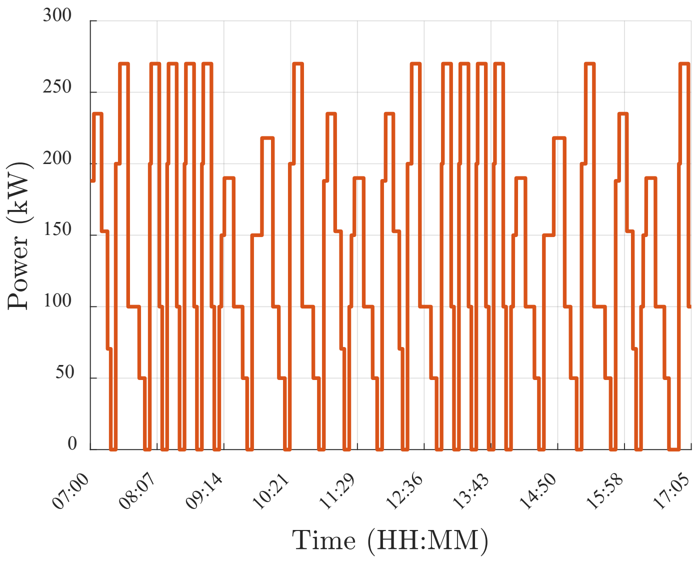

Figure 7. The modelled stack of 23 charging session profiles of EVs.

Impact of ambient temperature with EV load

Figure 8 illustrates the effect of EV charging on the thermal performance of a transformer with a non-EV load of 0.75 p.u. and inter-session time interval is 5 min, under ambient temperature variation from 30°C to 40°C. As shown, the relative ageing factor occasionally exceeds unity due to peak EV loads; however, this can be offset by periods of relative ageing rate below unity. As ambient temperatures rise through the day, the hotspot temperature of the transformer also increases, leading to a higher ageing rate. It should be noted that, in Figure 8, a constant 75% utilisation of transformer is considered. However, in practical scenarios, the heating pattern is typically more dynamic. For example, the transformer would likely operate at a cooler temperature during the early morning hours and gradually heat up as the load increases throughout the day. Such realistic variations in loading patterns would result in revised lower temperatures.

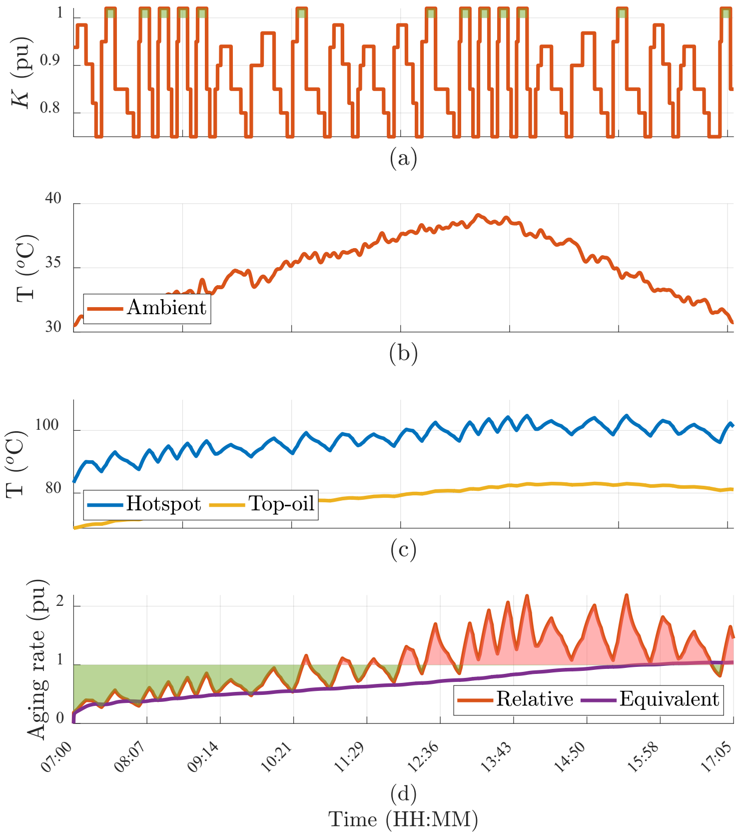

Figure 8. EV charging impact on thermal performance of transformer using conventional Kraft paper, for non-EV load of 0.75 p.u., ambient temperature 30°C to 40°C with 5 min of idle time between charging sessions (a) Load factor, K (b) ambient temperature, θ_a (c) hotspot temperature, θ_h and top-oil temperature, θ_o and (d) ageing rate.

Table 4 shows the impact of ambient temperatures on the transformer thermal performance, when inter-session time interval is 5 min. A non-EV load of 0.75 p.u. is applied beforehand, with the assumption that the transformer has already reached its steady-state temperature for this load before the first EV charging session starts. Each row represents a distinct scenario where the parameters are calculated using the IEC 60076-7 thermal model for a specific ambient temperature range. As seen in Table 4, with the ambient temperature increases from 15-25°C to 35-45°C, the maximum hotspot temperature increases from 89.8°C to 109.8°C, while the maximum top-oil temperature rises from 68.1°C to 88°C. This results in equivalent ageing factor rise by almost 9 times (from 0.19 to 1.88). This highlights that higher ambient temperatures significantly accelerate transformer ageing and result in increased internal temperatures.

Table 4. The impact of ambient temperatures on the transformer thermal performance, when inter-session time interval is 5 minutes and non-EV load is 0.75 p.u.

Ambient temperature range	Maximum ageing factor	Equivalent ageing factor	Maximum hotspot temperature	Maximum Top-oil temperature
15-25 °C	0.39	0.19	89.8 °C	68.1 °C
20-30 °C	0.68	0.33	94.7 °C	73.0 °C
25-35 °C	1.23	0.58	99.8 °C	78.1 °C
30-40 °C	2.19	1.04	104.8 °C	83.1 °C
35-45 °C	3.88	1.88	109.8 °C	88 °C

To optimise transformer capacity utilisation, power dispatch for EVs can be adjusted based on ambient temperature variations. Transformer capacity can be maximised during cooler periods and reduced during higher ambient temperatures to manage performance and ageing impacts effectively.

Impact of non-EV load

Table 5 presents the impact of uncontrolled power dispatch for an EV charging station on transformer thermal performance with varying non-EV loads. Each row corresponds to 23 EVs sequentially charged with a 5-minute intersession interval under the same ambient temperature pattern (25-35°C), while the non-EV load changes.

As the non-EV load increases, several key trends can be observed. There is a steep rise in the ageing factor as the non-EV load increases, highlighting the cumulative stress on the transformer. Table 5 illustrates that, as the transformer non-EV load increases from 0.6 p.u. to 1.0 p.u., the hotspot temperature rises from 85.3°C to 127.8°C, and the top-oil temperature increases from 68.7°C to 96.4°C. Correspondingly, the equivalent ageing factor grows from 0.12 to 13.94, demonstrating that higher non-EV loads significantly raise internal temperatures and accelerate transformer ageing. This trend can be explained by the steady nature of the load, where sustained increase in load lasting more than two hours exceeds the thermal time constant of the transformer oil. Such prolonged loading leads to greater heating effects and accelerated ageing compared to shorter, transient load peaks, such as those from EV charging.

Table 5. The effect of non-EV load on transformer thermal performance when EV charging station power is delivered as demanded without control. The inter-session interval is 5 minutes, with an ambient temperature range of 25-35°C.

Non-EV load	Maximum ageing factor	Equivalent ageing factor	Maximum hotspot temperature	Maximum Top-oil temperature
0.6 p.u.	0.23	0.12	85.3 °C	68.7 °C
0.7 p.u.	0.69	0.34	94.7 °C	74.8 °C
0.8 p.u.	2.27	1.1	105.1 °C	98.6 °C
0.9 p.u.	8.10	3.72	116.1 °C	88.7 °C
1.00 p.u.	31.18	13.94	127.8 °C	96.4 °C

Table 6. The impact of EV congestion at the charging station, represented by the idle time; the duration between end of charging of one EV and start of charging of the next EV. (Ambient Temperature: 30°C to 40°C, non-EV load of 0.75 p.u. and 23 EVs charged Back-to-Back with varying idle duration between charge sessions).

Idle duration between charging sessions	Maximum ageing factor	Equivalent ageing factor	Maximum hotspot temperature	Maximum Top-oil temperature
2 min	2.43	1.17	105.7 °C	83.6 °C
5 min	2.20	1.06	104.8 °C	83.1 °C
10 min	1.95	0.92	103.8 °C	82.3 °C
15 min	1.76	0.81	102.9 °C	81.7 °C

Impact of idle time between EV charging sessions

Table 6 illustrates the impact of EV congestion at the charging station, which is represented by the time duration between the end of one EV's charging session and the start of the next, where 23 EVs are charged sequentially with a constant interval between sessions. For example, the first row in Table 6 represents 23 EVs charged at the station with a 2-minute gap between sessions, a high congestion scenario. The ambient temperature ranges between 30°C and 40°C. Moreover, a prior non-EV load of 0.75 p.u. is considered, and it is assumed that the transformer reaches steady-state temperature corresponding to this load before the first EV charging session begins.

Observing Table 6, as the idle time between charging sessions increases from 2 minutes to 15 minutes, which means higher to lower congestion scenario, the hotspot temperature decreases from 105.7°C to 102.9°C, while the top-oil temperature reduces from 83.6°C to 81.7°C. Correspondingly, the maximum ageing factor decreases from 2.43 to 1.76, and the equivalent ageing factor drops by 30.8%, from 1.17 to 0.81. The natural inter-session interval between the end of one EV charging session and the start of the next, which typically involves a few minutes of changeover time, can help reduce the high ageing factor associated with peak power demand. This is particularly beneficial when EVs with high acceptance rates draw significant power, as the idle time reduces thermal stress and mitigate the impact of rapid load increases. This insight also highlights an additional degree of freedom, where charging stations can introduce short rest periods to help reduce the accelerated ageing of transformer insulation. This indicates that longer idle durations allow the transformer to dissipate heat more effectively, thereby reducing internal temperatures and slowing the ageing process.

Transformer Utilisation and Additional EV Chargers

This section assesses the number of 250 kW EV chargers can be deployed on a 1 MVA transformer before the year-on-year (y/y) ageing factor exceeds 1 given existing transformer load and proposed EV congestion (idle time).

Figure 9 presents the ageing and thermal behaviour of a 1 MVA transformer operating with a single 250 kW charger over the week of January 1–7, 2023, in Byron Bay, NSW. The data shows that when no EV charging occurs, the transformer's insulation ageing rate remains below 1. The shaded green area highlights the available unused capacity that helps offset periods of elevated ageing rates (greater than 1) during high-power EV charging.

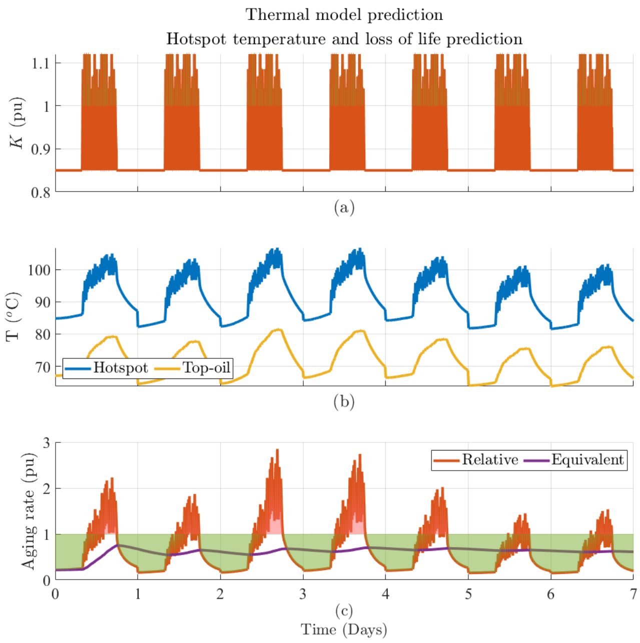

Figure 9. Thermal performance and ageing analysis of a transformer over one week (January 1–7, 2023) in Byron Bay, NSW, based on representative EV charging profiles. A high non-EV utilisation of transformer at 85% and high EV congestion with new charging sessions starting within 5 minutes, from 8 AM to 6 PM.

The observations from Figure 9 are that the transformer benefits from overnight cooling and the variable charging patterns of EVs. During a charging session, only a few minutes are typically spent at the EV acceptance rate—the maximum power at which the EV battery can charge. Additionally, there are cooling intervals between charging sessions, such as when one EV is unplugged, and another begins charging. These factors prevent the transformer from experiencing continuous overloading. The transformer does not heat up as much as it would under a constant conventional load sustained for durations longer than the transformer's thermal time constants.

Three EV congestion scenarios are created to analyse the impact of adding EV chargers on a transformer with varying levels of existing utilisation. Low EV congestion corresponds to fewer EVs on the roads hence the time duration between two EV charging sessions is 15 minutes. For medium EV congestion scenario this intersession interval is 10 minutes while the high congestion scenario represents the case when most of the vehicles on roads are EVs and the EV charging sessions end and start within 5 minutes.

Scenario 1: Low EV congestion

Table 7 illustrates a low-congestion scenario in which the interval between consecutive EV charging sessions is 15 minutes. The table highlights the impact of installing increments of 250 kW chargers on a 1 MVA transformer, specifically focusing on the consequences for transformer insulation ageing and total energy delivered as an EV charging service over the year. This analysis considers different levels of existing non-EV load utilisation. The data is from 2023 in Byron Bay, NSW.

Table 7. Low congestion scenario where time between consecutive EV sessions is 15 min. Consequences on transformer insulation ageing with respect to number of 250 kW chargers installed on a 1 MVA transformer for various levels of existing non-EV utilisation. (Location: Byron Bay, NSW. Year 2023).

Non-EV Utilisation	No. of EV chargers	Equivalent ageing factor Y/Y (p.u.)	Total EVSE Energy delivered (MWh)
25%	1 × 250 kW	0.0018	479
	2 × 250 kW	0.0035	959
	3 × 250 kW	0.0087	1438
	4 × 250 kW	0.029	1977
50%	1 × 250 kW	0.011	479
	2 × 250 kW	0.027	959
	3 × 250 kW	0.089	1438
	4 × 250 kW	0.39	1977
75%	1 × 250 kW	0.14	479
	2 × 250 kW	0.41	959
	3 × 250 kW	1.73	1438
	4 × 250 kW	9.69	1977

Each entry in the column "Equivalent ageing Factor Y/Y (p.u.)" of Table 7 represents the results of extending the seven-day simulation shown in Figure 9 to an entire year, providing the equivalent yearly ageing rate. Total energy delivered for charging over the year is also tabulated.

It can be observed from Table 7 that up to 4 250 kW chargers can be added for a 1MVA transformer with utilisation of 25% and 50% without the cumulative yearly ageing exceeding 1 p.u. In case of a high utilisation of 75%, two 250 kW chargers can be added while keeping cumulative ageing below 1 p.u. Each additional charger delivers 479 MWh of energy annually for EV charging. In low utilisation scenarios (25% and 50%), the transformer can support up to four 250 kW EV chargers delivering 1977 MWh of annual energy for EV charging without requiring an upgrade.

Table 8 shows the number of instances when hotspot temperature goes above defined threshold values for specified duration for low congestion scenario, for the transformer location in Byron Bay, NSW. This analysis highlights the frequency of extreme thermal conditions under the given scenario. The table shows the number of instances when temperature exceeds 98°C for 1 hour. There are 8736 possible instances (time slots of 1 hour) in total analysed data window of 1 year. The table also reports instances when hotspot temperature surpasses 120°C for 30 minutes (out of a total of 17472 possible instances) and instances of hotspot temperature over 140°C for 15 minutes (out of a total of 34944 possible instances).

Table 8. Low congestion scenario: number of instances when hotspot temperature goes above defined threshold values for specified duration. (Location: Byron Bay, NSW. Year 2023).

Non-EV Utilisation	No. of EV chargers	Instances of Hotspot temperature over 98°C for 1 hour (Total: 8736)	Instances of Hotspot temperature over 120°C for 30 minutes (Total: 17472)	Instances of Hotspot temperature over 140°C for 15 minutes (Total: 34944)
25%	1 × 250 kW	0	0	0
	2 × 250 kW	0	0	0
	3 × 250 kW	0	0	0
	4 × 250 kW	0	0	0
50%	1 × 250 kW	0	0	0
	2 × 250 kW	0	0	0
	3 × 250 kW	0	0	0
	4 × 250 kW	0	0	0
75%	1 × 250 kW	0	0	0
	2 × 250 kW	5	0	0
	3 × 250 kW	1063	0	0
	4 × 250 kW	3551	81	0

The key insights from the table for a 1 MVA transformer under the given low EV congestion scenario are as follows.

- The hotspot temperature does not exceed 980C for even four 250 kW chargers for utilisation of 25% or 50%.
- For a high utilisation case of 75%, installing one 250 kW never exceeds hotspot temperature beyond 980C.
- For a high utilisation case of 75%, the hotspot temperature exceeds 98°C for two EV chargers in 5 1-hour instances (0.06%), for three chargers in 1063 instances (12%), and for four chargers in 3551 instances (40.6%).
- Hotspot temperature only exceeds 1200C in case of high 75% utilisation with four 250 kW chargers for 81 times for 30 minutes which is 0.46% of the time spent above 1200C over the year.
- The temperature never exceeded 1400C for either of the utilisation or number of EV charger combination studied in this table.

Scenario 2: Medium EV congestion

Table 9 presents a medium-congestion scenario with a 10-minute interval between consecutive EV charging sessions. It shows the effects of adding increments of 250 kW chargers to a 1 MVA transformer on insulation ageing and the total annual energy delivered for EV charging. The analysis accounts for varying levels of existing non-EV load utilisation and is based on weather data from Byron Bay, NSW, for the year 2023.

Table 9 shows that, like the low EV congestion scenario, up to four 250 kW chargers can be added to a 1 MVA transformer with 25% or 50% utilisation without the cumulative yearly ageing exceeding 1 p.u. However, for high non-EV utilisation of 75%, the cumulative yearly ageing exceeds 1 p.u. when more than two 250 kW chargers are installed. Table 10 details the frequency of instances where the hotspot temperature surpasses defined thresholds for specific durations under the medium-congestion scenario at the transformer located in Byron Bay, NSW.

Table 9 . Medium congestion scenario where time between consecutive EV sessions is 10 min. Consequences on transformer insulation ageing with respect to number of 250 kW chargers installed on a 1 MVA transformer for various levels of existing non-EV utilisation. (Location: Byron Bay, NSW. Year 2023).

Non-EV Utilisation	No. of EV chargers	Equivalent ageing factor Y/Y (p.u.)	Total EVSE Energy delivered (MWh)
25%	1 × 250 kW	0.0018	479
	2 × 250 kW	0.0037	959
	3 × 250 kW	0.010	1438
	4 × 250 kW	0.038	1977
50%	1 × 250 kW	0.011	479
	2 × 250 kW	0.03	959
	3 × 250 kW	0.11	1438
	4 × 250 kW	0.57	1977
75%	1 × 250 kW	0.14	479
	2 × 250 kW	0.48	959
	3 × 250 kW	2.32	1438
	4 × 250 kW	15.22	1977

Table 10. Medium congestion scenario: number of instances when hotspot temperature goes above defined threshold values for specified duration. (Location: Byron Bay, NSW. Year 2023).

Non-EV Utilisation	No. of EV chargers	Instances of Hotspot temperature over 98°C for 1 hour (Total: 8736)	Instances of Hotspot temperature over 120°C for 30 minutes (Total: 17472)	Instances of Hotspot temperature over 140°C for 15 minutes (Total: 34944)
25%	1 × 250 kW	0	0	0
	2 × 250 kW	0	0	0
	3 × 250 kW	0	0	0
	4 × 250 kW	0	0	0
50%	1 × 250 kW	0	0	0
	2 × 250 kW	0	0	0
	3 × 250 kW	0	0	0
	4 × 250 kW	4	0	0
75%	1 × 250 kW	0	0	0
	2 × 250 kW	125	0	0
	3 × 250 kW	2029	0	0
	4 × 250 kW	3690	753	6

Some observations from Table 10, corresponding to the medium EV congestion scenario on a 1 MVA transformer are outlined below.

- The hotspot temperature does not exceed 980C for even four 250 kW chargers if the utilisation is 25%.
- For 50% utilisation, hotspot temperature exceeds 980C for four 250 kW chargers for 4 1-hour instances, that accounts to 0.04% time spent over 980C for the entire year.
- For a high utilisation case of 75%, installing one 250 kW never exceeds hotspot temperature beyond 980C.
- For a high utilisation case of 75%, the hotspot temperature exceeds 98°C for two EV chargers in 125 1-hour instances (1.4%), for three chargers in 2029 instances (23%), and for four chargers in 3690 instances (42%).
- Hotspot temperature exceeds 1200C in case of high 75% utilisation, and four 250 kW EV chargers, for 753 times for 30 minutes which is 4.3% of the time spent above 1200C over the year.
- The temperature exceeded 140°C only at 75% utilisation with four 250 kW EV chargers, occurring 6 times for 15 minutes, which corresponds to 0.017% of the total annual time.

Scenario 3: High EV congestion

Table 11 analyses a high-congestion scenario characterised by a 5-minute gap between successive EV charging sessions. It examines the impact of adding increments of 250 kW chargers to a 1 MVA transformer on insulation ageing and the total annual energy supplied for EV charging. The study considers different non-EV load utilisation levels and is based on weather data from Byron Bay, NSW, for the year 2023.

Like the low and medium EV congestion scenarios, the results indicate that a 1 MVA transformer can support up to four 250 kW chargers at 25% or 50% utilisation without exceeding a cumulative yearly ageing of 1 p.u. However, at 75% non-EV utilisation, the yearly ageing surpasses 1 p.u. when more than two 250 kW chargers are added.

Table 11. High congestion scenario where time between consecutive EV sessions is 5 min. Consequences on transformer insulation ageing with respect to number of 250 kW chargers installed on a 1 MVA transformer for various levels of existing non-EV utilisation. (Location: Byron Bay, NSW. Year 2023).

Non-EV Utilisation	No. of EV chargers	Equivalent ageing factor Y/Y (p.u.)	Total EVSE Energy delivered (MWh)
25%	1 × 250 kW	0.0019	479
	2 × 250 kW	0.0040	959
	3 × 250 kW	0.012	1438
	4 × 250 kW	0.055	1977
50%	1 × 250 kW	0.012	479
	2 × 250 kW	0.034	959
	3 × 250 kW	0.15	1438
	4 × 250 kW	0.94	1977
75%	1 × 250 kW	0.15	479
	2 × 250 kW	0.58	959
	3 × 250 kW	3.42	1438
	4 × 250 kW	28.26	1977

Table 12 provides the occurrence of instances where the hotspot temperature exceeds specified thresholds for set durations in a high-congestion scenario at the 1 MVA transformer in Byron Bay, NSW. Key observations from Table 12 related to the high EV congestion scenario are summarised below.

- The hotspot temperature does not exceed 98oC for even four 250 kW chargers if the utilisation is 25%.
- For 50% utilisation, hotspot temperature exceeds 98oC for four 250 kW chargers for 391 1-hour instances, that accounts to 4.5% time spent over 98oC for the entire year.
- For a high utilisation case of 75%, installing one 250 kW never exceeds hotspot temperature beyond 98oC.
- For a high utilisation case of 75%, the hotspot temperature exceeds 98°C for two EV chargers in 526 1-hour instances (6%), for three chargers in 2735 instances (31.3%), and for four chargers in 3572 instances (41%) over the year.
- At 75% high utilisation, the hotspot temperature surpasses 120°C in 40 instances (0.2%) for 30-minute intervals with three EV chargers. For four chargers, it exceeds 120°C in 2770 instances, that accounts for 16% of the total annual time above this threshold.
- The temperature exceeded 140°C only at 75% utilisation with four 250 kW EV chargers, occurring 353 times for 15 minutes, which corresponds to 1% of the time temperature exceeded 140°C over the year.

Table 12. High congestion scenario: number of instances when hotspot temperature goes above defined threshold values for specified duration. (Location: Byron Bay, NSW. Year 2023).

Non-EV Utilisation	No. of EV chargers	Instances of Hotspot temperature over 98°C for 1 hour (Total: 8736)	Instances of Hotspot temperature over 120°C for 30 minutes (Total: 17472)	Instances of Hotspot temperature over 140°C for 15 minutes (Total: 34944)
25%	1 × 250 kW	0	0	0
	2 × 250 kW	0	0	0
	3 × 250 kW	0	0	0
	4 × 250 kW	0	0	0
50%	1 × 250 kW	0	0	0
	2 × 250 kW	0	0	0
	3 × 250 kW	0	0	0
	4 × 250 kW	391	0	0
75%	1 × 250 kW	0	0	0
	2 × 250 kW	526	0	0
	3 × 250 kW	2735	40	0
	4 × 250 kW	3572	2770	353

Control strategy

As discussed in previous sections, multiple factors contribute to temperature rise and insulation ageing, including EV charging patterns, ambient temperature conditions, and non-EV loads. Therefore, load management and scheduling are crucial for maintaining transformer health and preventing accelerated ageing. To address this, developing a control strategy that effectively mitigates the impact of these factors is essential. In this section, control strategy is presented to manage the transformer's thermal limits by dynamically adjusting the power delivered to EVs based on charging demand and hotspot temperature.

This control strategy follows the principle outlined below to manage power for EV charging.

Control principle: *A four-level hysteresis, with defined hotspot temperatures at each level, is implemented to dispatch different power* levels *based on the range in which the hotspot temperature falls.*

Following this control strategy, EVs may receive a certain percent of power ranging from 0-100%, in steps of 25%, depending upon the hotspot temperature of the transformer. Utilising multiple hotspot temperature levels for decision-making enables precise control and the potential for enhanced capacity dispatch. This approach also functions as a predictive mechanism, allowing for a gradual reduction in power as temperatures rise throughout the day or when loads significantly increase.

Figure 10 illustrates the temperature and ageing rate when the power supplied to EVs is reduced in 25% increments as the temperature reaches the next level in a four-level hotspot temperature hysteresis, with thresholds set at 100 °C, 103 °C, 107 °C, and 110 °C. Over a 10-hour period, the total energy demand from 23 EVs was 1364 kWh, with 1262 kWh delivered, accounting for 92% of the total demand. The control strategy results in EV charging at 0.75 of requested charge for 20%, 0.50 of requested charge for 5% and supplied full demand for the remaining duration. EVs are supplied close to their acceptance rate or demand for over 95% of the time, enhancing customer satisfaction. Throughout this period, the equivalent ageing factor is measured at 0.93, signifying that a higher capacity is dispatched. It is important to note that the charging dispatch and ageing rate will depend on the EV charging patterns and the hotspot temperature hysteresis thresholds. These thresholds can be adjusted higher or lower based on specific circumstances, which will in turn affect the dispatched capacities for EV charging. For instance, if the transformer has been operating at low utilisation for months or years prior to the installation of EV charging and has experienced significantly lower ageing compared to the time since commissioning, the hotspot temperature hysteresis thresholds could be set higher to take advantage of the lower ageing periods.

To complement the proposed multi-level hysteresis control strategy, customer-centric incentives can be integrated to encourage demand flexibility when charging power reductions are recommended. When charging rates are reduced or sessions are extended, customers could be incentivised with offers such as discounts on nearby forecourt services (e.g., coffee or snacks) if a refreshment canter is available or reduced tariffs for agreeing to delayed charging. This strategy promotes customer choice while supporting asset longevity, operational efficiency, and overall satisfaction.

Dynamic connections agreement and OCPP

Dynamic connection agreements will play a pivotal role in translating the potential of this project into a real-world impact. OCPP 2.0 and ISO 15118 form the backbone of the framework to achieve this. OCPP 2.0 (Open Charge Point Protocol 2.0) is a communication protocol that enables the exchange of information between electric vehicle charging stations and central systems, supporting features like smart charging, remote control, and real-time monitoring. ISO 15118 is a standard for communication between electric vehicles and charging stations, enabling secure and seamless charging, including features like plug-and-charge, dynamic charging power negotiation, and integration with grid services.

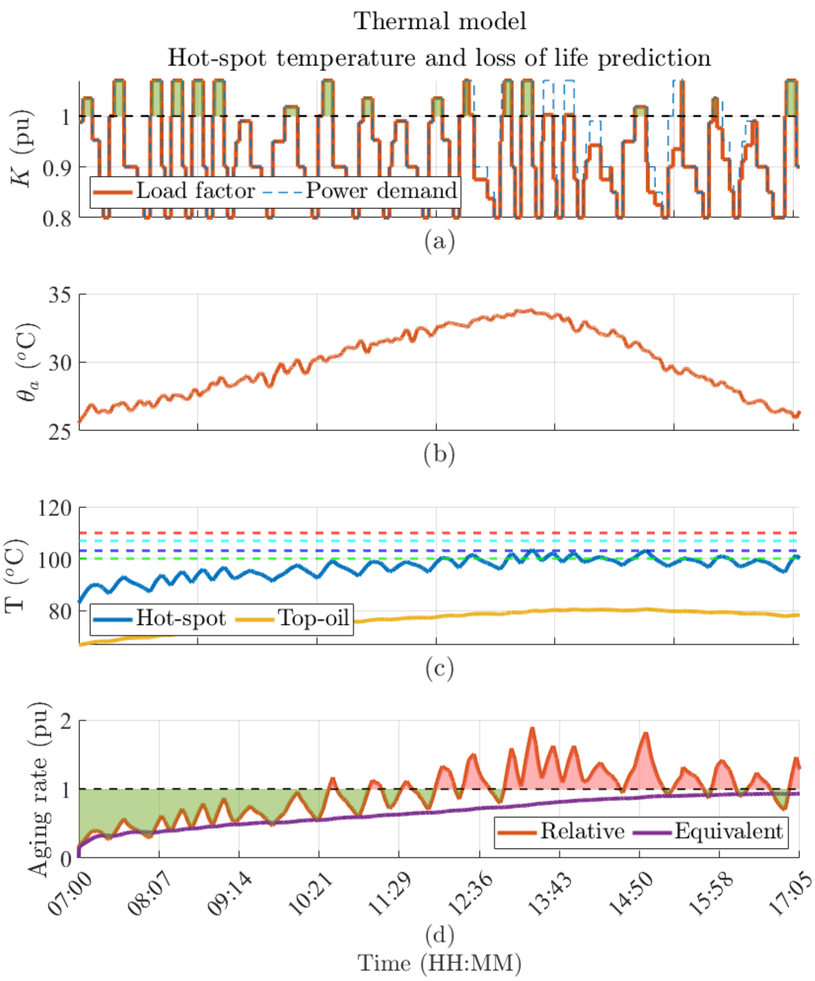

Figure 10. Transformer thermal performance and ageing rate under multilevel hysteresis control, for Kraft paper insulation. Conditions: non-EV load 0.8 p.u. and ambient temperature range 25-35 °C.

The integration of OCPP 2.0 and ISO 15118 provides a robust foundation for establishing dynamic connection agreements that optimise transformer capacity utilisation and ensure efficient electric vehicle (EV) charging. OCPP 2.0, particularly its "Smart Charging" capabilities, enables charging stations to communicate with backend systems to dynamically adjust power delivery based on real-time transformer conditions. This allows for intelligent load management, ensuring that charging power is distributed efficiently without exceeding thermal limits or causing grid instability.

OCPP 2.0, particularly through its "Smart Charging" capabilities (Section K), facilitates real-time communication between EV chargers and their backend systems. This allows for dynamic adjustments of charging parameters such as maximum current, power levels and charging schedules during the charging process. For example, a backend system can send a SetChargingProfile command via OCPP 2.0 to a charging station, specifying a time-based power limit curve to prevent transformer overloading during peak hours. ISO 15118 complements this by enabling communication between EVs and charging stations. Together, these standards facilitate the dynamic allocation of charging power and real-time load balancing that can help in the efficient utilisation of transformer capacity.

Workflow Summary

- Backend detects overheating and sends a SetChargingProfile to limit power (OCPP 2.0).
- Charger updates its limits and communicates them to EVs (ISO 15118).

EVs adjust their charging rates dynamically, ensuring the transformer stays within safe operating limits. Several commercial tools and platforms support EV charger management including dynamic load balancing, OCPP compatibility, and integration with grid signals. These include ChargePoint Cloud, EVBox Everon and Ampcontrol etc. These platforms interact with OCPP to facilitate seamless communication and control between chargers and backend systems. By leveraging OCPP's features, they can dynamically manage charging profiles through commands like SetChargingProfile, adjusting power delivery based on grid capacity or transformer constraints.

Instrumentation needs

Accurate load factor (K) and temperature are important for implementing control algorithms to dynamically manage transformer temperature and ageing rate. Various levels of instrumentation can be used to achieve real-time thermal performance monitoring of transformers, as provided in Table 13. The table outlines different instrumentation options, highlighting their advantages and drawbacks. Option 1 involves measuring current and ambient temperature while estimating hotspot and top-oil temperatures using transformer thermal model, in this case IEC 60076-7, which is computationally complex but cost-effective. Option 2 includes direct hotspot temperature measurement, allowing for more accurate control strategies, though still estimating top-oil temperature, with low complexity and a higher cost. Option 3 offers easier top-oil temperature sensing but relies on modelled hotspot temperature, retaining some computational complexity. Lastly, Option 4 provides the most accurate results by directly measuring all parameters, eliminating the need for using thermal models for online monitoring, but comes with the highest cost.

Table 13. Instrumentation options and their pros and cons.

Measurement	Current	ambient temperature	Hotspot temperature	Top-oil temperature	Comments
Option 1	✓	✓	✗	✗	Hotspot and top-oil temperature estimated by model, computationally complex, lowest cost
Option 2	✓	✓	✓	✗	Control strategies can be accurate, top-oil temperature estimated by model, low complexity, higher cost
Option 3	✓	✓	✗	✓	Hotspot temperature estimated by model, computationally complex, easier temperature sensing
Option 4	✓	✓	✓	✓	More accurate, model not needed for online monitoring, highest cost

Accessories and Associated Cables: Potential Limitations and Considerations

While increasing transformer utilisation to support EV charging is crucial, it is equally important to consider the potential limitations imposed by associated accessories and ancillaries such as bushings, cables, fuses etc. These components play a critical role in the safe and efficient operation of the transformer and may become limiting factors when the transformer operates closer to its thermal or load capacity.

According to IEC 60076-7, bushings, cable-end connections, tap-changing devices, and leads may limit transformer operation when loaded beyond 1.5 times the rated current. Oil expansion and increased pressure can also impose operational constraints. gassing can occur in condenser-type bushings when the insulation temperature exceeds approximately 140°C.

IEEE Std C57.91-2011 highlights the impact of overloading transformers on components like oil-impregnated, paper-insulated, capacitance-graded bushings. Bushings are typically designed for a maximum hottest-spot temperature of 105°C at rated current with a transformer top-oil temperature of 95°C over 24 hours. Overloading beyond the nameplate rating can exceed these limits, leading to issues such as internal pressure buildup, gasket ageing, increased power factor, gassing above 140°C, and thermal runaway. However, the guide also notes that bushings are less prone to overload effects compared to transformer windings due to factors like sealed construction, drier insulation, and higher current ratings. IEEE Std C57.91-2011 recommends overload limits for safe operation: for ambient air temperature of 40°C and transformer top-oil temperature of 110°C, maximum current should be less than twice the rated bushing current, and a bushing hottest-spot temperature should not exceed 150°C.

Therefore, to support higher EV charging demands by momentarily overloading transformers, it is crucial to account for the limitations of accessories such as bushings, cables, and tap-changers. A possible solution could be to enhance these components' ratings or implement the control strategies to minimise the duration of overloading beyond 1.5 or operation above 150°C, by reducing EV charging power using OCPP when such instances occur. Upgrading critical accessories, when possible, could offer a cost-effective alternative to upgrading the entire transformer.

Charging Etiquette

A recent study undertaken by UNSW's Digital Grid Futures Institute considered the enablers and the barriers to public attitudes to charging etiquette [7]. Figure 11 is an excerpt from this study highlighting the conclusions from two studies.

Study 1 point 3 and 4 clearly highlights the importance of customers gaining confidence in the charging infrastructure. To an extent this means that the customer needs to feel confident in the time it takes to deliver the necessary charge and what that charge would be. This category of users' needs to be able to access a basic mode that clearly defines time and charge for their vehicle with adaptive changes taking place during the charging time likely to impact on their confidence of the charging equipment and the potential that they might feel unsure of the process.

Study 2 points 4 and 5 also highlight the need for customers to have a clear and consistent interface with all types of charging infrastructure. In many respects this reflects current practices at fuel stations: common looking delivery machines, forecourt similarities, shopping possibilities, basic sets of maintenance tools and consumables available at the outlet, pricing signage having common features and layout making it easier to understand what the charge will be once you have completed.

This latter point will become more of a challenge in the short term at least.

Both studies are helping to define what customers are seeking to experience at charging stations, much of which is relevant to the consumer interface and the impact that control of charging might have on the customer that is still learning about the system and its control. The presented control strategy is evaluated based on parameters impacting customer satisfaction, such as the duration customers are denied charging or receive a reduced charging rate compared to the vehicle's demand, both of which influence total time spent at the charging station.

Study 1:

1. Enhancing EV drivers' perception of control by increasing driver's confidence in correctly using charging infrastructure through clean instructions, demonstration, and guidance around charging etiquette.
2. Provide *real-time updates of multiple brands of charging station availability in one source* (app, monitor, GPS) to allow EV drivers to make informed decisions about where and when to charge.
3. Addressing negative attitudes towards charging infrastructure through *improving the reliability of charging infrastructure*. Create processes for drivers to easily report broken charging infrastructure, schedule regular maintenance of charging infrastructure and have technicians on standby to fix charging stations located in rural areas.
4. Invest in improving design of charging infrastructure to be easy and *consistent across brands and companies. Governments or EV organisations may choose to create a more standardised approach to ensure similarity between different companies.*
5. Optimise the physical layout of charging stations by increasing the number of bays and types of charging speeds to make it easier and more convenient for EV drivers to use the charging stations. Stakeholders should investigate the *suitability of charging stations for a wide range of EV drivers*.
6. Building charging stations near amenities, restaurants, rest stops, parks, shopping centres to provide EV drivers with things to do while they charge their vehicles.

Study 2:

1. To improve the environmental context and resource, enhance the *visibility and accessibility of charging stations, make charging more convenient, build more infrastructure* (i.e. limit the distance between them).
2. Developing a *range of targeted resources and media campaigns, provide expos, instructional videos to increase knowledge and awareness of charging etiquette within the general population*.
3. Create and implement signage like council carparks that list acceptable or unacceptable practices for drivers to follow (See Appendix H for example).
4. Utilise technology to help facilitate good charging behaviours such as sending the driver a text message when charging is complete with a warning to collect your vehicle or move your vehicle after 5 to 10 minutes. Implement incremental idle fees. Provide drivers with resources to communicate with each other, whether it's through the charging app or QR code, protect the anonymity of both drivers as some drivers may not feel comfortable sharing their details.
5. Place a stronger focus on the enforcement of charging etiquette, provide warnings, penalties, and fines in a similar manner to those who overstay or park in disabled parking. Provide fines for drivers who fail to move their EV after 15 minutes of charging session being complete or penalise drivers who charge more than 80% during busy period by making them pay a higher rate.

Figure 11. Outcomes from two studies undertaken by A. Shinde et al. to determine the challenges associated with charging etiquette [7].

Harmonic currents effect on transformer thermal limits

The IEEE Std C57.110 provides a guidance on loading capability of distribution transformers supplying non-sinusoidal currents. The elevated harmonic content in the load current of the transformers results in increased eddy current losses within the windings and structural parts linked by the transformer's leakage flux, which in turn raises the operating temperatures. The document IEEE Std C57.110 provides methods to calculate power losses accounting for harmonic current factor. With a current harmonic content of 5%, eddy current losses can be as much as 2.73 times higher than those caused by a pure sinusoidal current. Similarly, other stray losses also increase. These losses must be accounted for when calculating temperature rises in a transformer.

DC fast chargers are power electronic converters that can generate harmonic currents. A study in [8] highlights power quality issues, including harmonic distortion and super harmonics (2-150 kHz) caused by high switching frequencies, reaching up to 3% of the fundamental frequency. In [9], the influence of harmonics is considered for estimating the increases in hotspot and top-oil temperatures in a transformer while supplying EV loads. While specific numerical values for the contribution of harmonics to temperature rise are not provided, it is acknowledged that they do contribute to these increases.

Conclusions and future research opportunities

This initial feasibility project has demonstrated that there is significant untapped capacity available from transformers to address some of the challenges of electric vehicles fast charging, and more so in cooler climates or seasons when lower ambient temperatures allow even longer operation at levels above their nameplate rating whilst still regulating the equivalent ageing factors.

Utilising this capacity, transformers can be "overloaded" for short periods to accommodate peak EV loads without adversely affecting the transformer lifespan or scheduled maintenance or retirement. This study examined the impact of fast-charging EVs' short, high-power loads on the utilisation and ageing of 1 MVA distribution transformers, specifically assessing how many 250 kW chargers can be installed under different utilisation levels. Three congestion scenarios – low (15-minute gaps), medium (10-minute gaps), and high (5-minute gaps) – are analysed. Results show that the transformer's thermal inertia, overnight cooling, and intermittent EV charging prevent prolonged overloading. At 25% and 50% utilisation, up to four 250 kW chargers can operate without accelerated ageing, delivering 1977 MWh annually. However, at 75% utilisation, adding three or four chargers significantly accelerates ageing due to thermal constraints. The oil's thermal inertia filters peak load effects, moderating hot-spot temperature rise despite sudden load increases. The additional capacity estimate for EV charging is conservative, as transformers with diamond-dotted paper insulation are expected to offer enhanced thermal performance. Moreover, non-EV loads may allow for even more capacity to be dedicated to EV charging. The control strategies outlined in this report can serve as a valuable reference for implementing measures to effectively leverage this additional capacity.

In addition to the work listed below there are the items identified in the original proposal presented by Essential Energy and UNSW to RACE2030.

Further research would explore in more detail this additional transformer capacity and the methods by which it can be utilised. Future research should include the following.

- Establishment of two long-term reference sites for the study of EV loads and analyse the difference in thermal performance.
- Assess the heat run tests and their ability to provide useful parameters for online sensing models.
- Perform field tests, capturing the necessary data to assess control options and their performance as well as generating data that can be used to assess the improvements obtained.
- Comparison of ageing reduction to cost of network augmentation using traditional transformer limits.
- Determine value of dynamically managing transformer thermal limits to release extra capacity thereby avoiding infrastructure expenditure.
- Impact of utilising additional transformer capacity on auxiliary equipment.
- Quantification of increased power losses from transformer overload in terms of cost.
- Investigate the impact of harmonic currents from DC fast chargers on iron and copper losses, and their impact on transformer thermal performance.
- Using the data from the transformer test sites to improve the thermal model for EV peak loads.
- Research and develop thermal model suitable for distribution transformers and using these models for existing transformers to utilise untapped capacity.
- Consider cyclic rating and emergency rating of 1.5 and 1.8 p.u. and see the impact on loss of life.
- Investigate forced air cooling for leveraging extra capacity.

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