Investigation Into Non-invasive Temperature Condition Monitoring Of Electrical Equipment

Michael Betteridge

Dowon Kim
Electrical Engineering, Computing and Mathematical Sciences
Curtin University

Neil Bell
CEED Client: Chevron Australia Pty Ltd

Abstract

Typical infrared thermography (IRT) measurements and inspections require the opening of electrical panels to expose live components which has significant inherent safety risks. This project aims to investigate an alternative non-invasive external surface IRT (ESIRT) technique for predictive maintenance application within electrical enclosures. ESIRT is of interest to Chevron as a part of their Electrical Maintenance Optimisation Strategy which aims to execute condition monitoring strategies that maximise equipment useful life, in lieu of invasive alternatives requiring costly production outages or inherent safety risks. The objective of this project is to provide investigative conclusions for the efficacy of ESIRT to detect high resistance connection failure modes within a 37kW electrical enclosure. Thermal Final Element Analysis (FEA) using ANSYS software and experimental validation are used to establish external surface temperature distributions for analysis. FEA analysis demonstrated ESIRT can theoretically detect surface temperature changes from a high resistance connection within the 37kW enclosure. Coupled analysis and experimental investigation must be undertaken for the comparison and validation of the FEA findings before definitive investigative conclusions can be reached regarding the efficacy of ESIRT.

1. Introduction

Infrared Thermography (IRT) measures infrared radiation to indicate object temperature (Usamentiaga et al., 2014). IRT is a technique widely used within the Oil and Gas industry to indicate failing electrical equipment, however IRT inspections have significant inherent risks as they require the opening of electrical enclosures and removal of covers to expose personnel to live electrical components (Safe Work Australia, 2012). This study investigates an alternative non-invasive external surface IRT (ESIRT) technique for a predictive maintenance application within Direct On Line (DOL) starter enclosures. This uses IRT to condition monitor the external faceplate and detect temperature differentials associated with equipment failure modes.

Many oil and gas plants are under continuous 24/7 operation and electrical equipment maintenance is critical to reduce equipment failure incidences and unscheduled operational outages for improvements in safety and fire risk, production loss, and economic cost. Chevron is implementing an electrical maintenance optimisation strategy (EMOS) to outline a clear, safe, cost efficient, and industry compliant maintenance framework for their operations whilst they are still early on within their lifecycle. Intrinsic to EMOS is a desire to execute non-invasive condition monitoring strategies such as ESIRT, in lieu of costly invasive alternatives that require production outages or have inherent safety risks. To be considered for use within the new EMOS, the capabilities and limitations of the ESIRT must be evaluated.

There has been steady development and application of IRT for electrical equipment condition monitoring however this development has focussed on techniques requiring opening of electrical enclosures (Bagavathiappan et al., 2013). There are currently no holistic analyses or reviews in the literature for the capabilities and limitations of ESIRT for electrical enclosure condition monitoring. The only current literature examines technique limitations through real world examples of electrical panel infrared inspections without removal of covers but does not look at the technique for use within a condition monitoring approach against baseline measurements (TEGG, 2015). The primary objective of this project is to provide investigative conclusions for the efficacy of ESIRT as a condition monitoring technique to detect high resistance connection failure modes within a 37kW DOL starter modular enclosure before catastrophic failure and/or production outages.

To determine whether a high resistance connection within a DOL starter enclosure is detectable from ESIRT the thermal surface temperature signature of the equipment is required. This requires the analysis of enclosure heat transfer which takes place through conduction, convection, and radiation as seen in Figure 2. The primary forms thermally analysed are convection and radiation for electrical equipment. When an object's temperature difference is significant, the radiation quantity increases substantially and results in radiation being the predominant form of energy transfer (Popa et al., 2014). Additionally, smaller conductors have a reduced convection contribution to heat transfer, making radiation the major form of heat transfer from small connection faults to enclosure surfaces. Analytical heat transfer analysis is a complex and timely process, with coupled FEA and Computational Fluid Dynamics (CFD) analysis the most effective alternative.

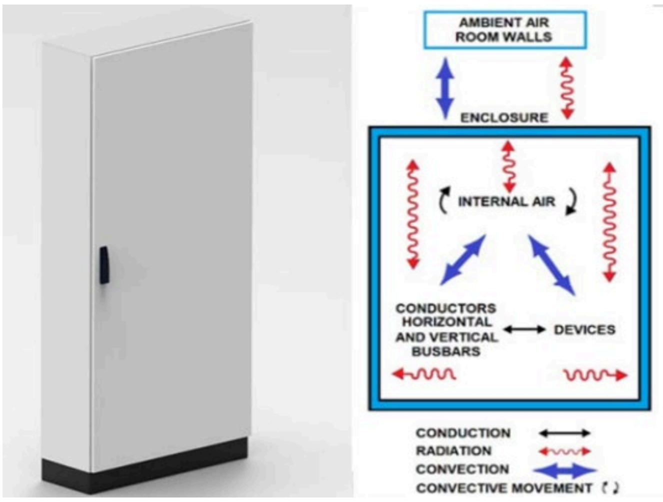

Figure 1 Heat Dissipation in Switchgear (Szulborski et al., 2021)

2. Modelling and Experimental Investigation

The primary investigation exercise is to determine if the front surface temperature difference for a 37kW DOL starter module with a high resistance connection is significant enough to be detectable by ESIRT. A combination of thermal analysis using ANSYS software and experimental validation are being conducted to establish external surface temperature distributions. Investigation commenced with a review of the module's overall geometry, materials, load size, ductance values, heat loss and baseline thermal data. This data allowed for accurate FEA model and experimental environment configuration. This process involved investigation into drawings, datasheets, site data, as well as in-person measurements of the individual module.

2.1 Modelling

2.1.1 Geometry and Meshing

A simplified geometry of the 37kW DOL starter module was created using Solidworks software. This geometry had two locations available at the contactor and rear lug connection for heating loads to be introduced as seen marked in Figure 2. The geometry was meshed with appropriate refinements introduced to ensure a high-quality mesh was established.

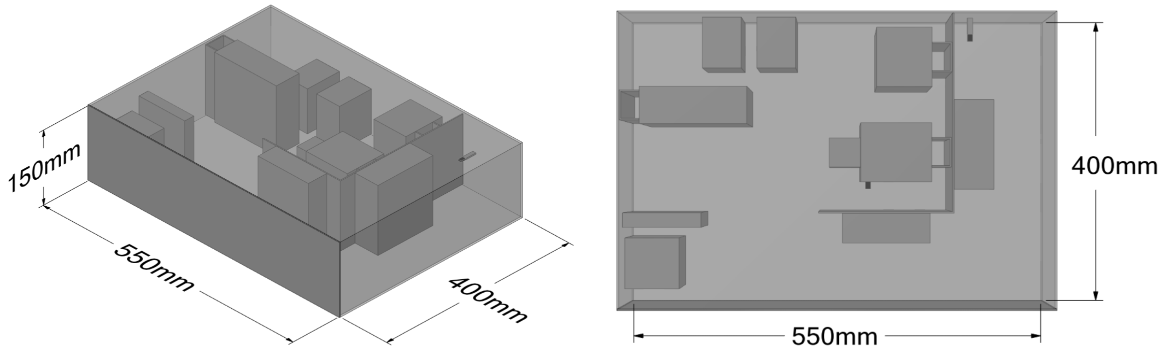

Figure 2 37kW DOL Starter Module Geometry Isometric and Layout

2.1.1 Setup Conditions

General material types were established from drawings, datasheets, and site personnel input. The model materials were set according to Table 1 using ANSYS GRANTA material database and emissivity literature (Transmetra, 2021).

Model Component	Material	Emissivity
Electrical Component Housings	Plastic PBT	0.95
Front Enclosure Face	Structural Steel (Painted)	0.95
Other Enclosure Faces	Galvanized Steel	0.23
Heated Connection	Copper (Oxidized)	0.6

Table 1 Model material setup data

Thermal survey data indicated the average operating temperature of the 37kW modules were between 29-38.1ºC. A 30ºC model ambient temperature was arbitrarily chosen from this data. Enclosure components were given heat generation rates estimated from power ratings that aligned their resulting temperatures at baseline with thermal survey observations. Industry data indicated high resistance connections with ductance readings of 900mΩ were at risk of thermal damage. As ESIRT is intended for predictive maintenance before failure, resistance values were modelled at values of 200, 400 and 600 mΩ. Heat generation was calculated using I^2R resistive heating as 20, 40 and 60W using a 10A per phase current from industry data.

Front surface temperature FEA results were taken for seven model permutations, inclusive of a baseline measurement with no additional heat source as well as 20, 40 and 60W heat sources at the contactor and rear lug locations. These result sets allowed for comparative data to be established for the difference in surface temperature apparent after the introduction of the heat source and the influence of the connection heating value and location variables. Further coupling of the FEA with CFD analysis will require meshing of the models fluid and an accurate analysis of the fluid heat transfer within the model, providing more accurate analysis results.

2.2 Experimental Investigation

The experimental setup seen in Figure 3 aims to collect real-world comparative data for validation of FEA analysis results to establish the efficacy of the ESIRT technique to identify surface temperature changes indicative of an internal high resistance connection.

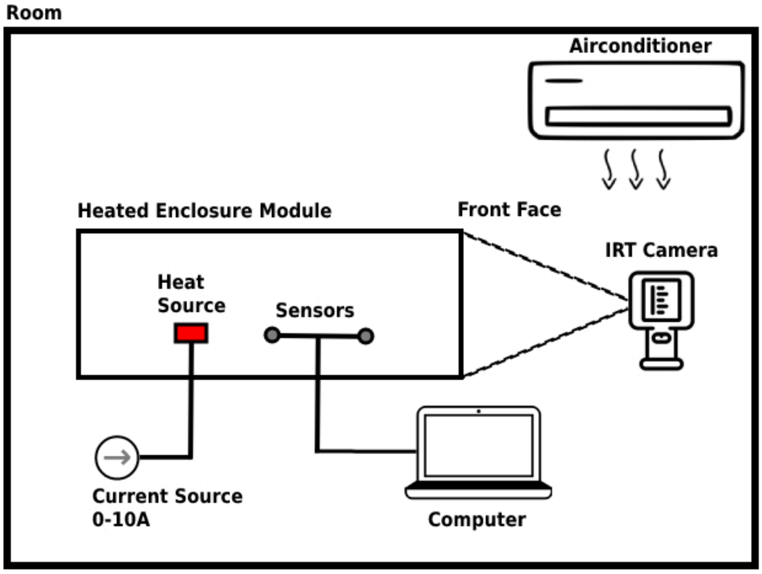

Figure 3 Experimental Setup Diagram

Testing is to be undertaken in a small, sealed room environment to reduce the influence of external environmental factors on experimental results. The ambient room temperature will be adjusted with an air conditioner to be 23.1ºC, in-line with industry thermal survey data.

The module for the experimental setup is the same as modelled within the FEA analysis to provide reliable corroborative data. To approximate the internal heating conditions of an in-service module, a variety of heating apparatus are introduced, including heating blankets within adjacent modules to approximate their heating effects as well as enclosure constant wattage heating cords and variable wattage air heaters. This equipment will be introduced individually until the appropriate 30ºC steady ambient condition is established at which point baseline IRT surface measurements will be taken. The high resistance connection will be setup as a 100W resistor connected through an AC VARIAC source to produce variable 20W, 40W and 60W heating at both locations. IRT measurements will be taken once steady state is reached for each heat source permutation, indicated by thermocouple measurement data.

A FLIR TG267 thermal imager will be used to collect front surface temperature signatures from a fixed position. A FLUKE 572-2 IR thermometer will also be used as an additional form of surface temperature measurement. Alongside this, temperature sensing thermocouples will be introduced within the enclosure that are linked back to a Labjack T7-Pro unit and computer to collect internal temperature data and identify steady state condition is achieved.

3. Results and Discussion

Figure 4 below illustrates the FEA analysis results for the front surface temperature distribution of the module for the four permutations of heat sources at the contactor. These results indicate a clear change in temperature from the high resistance connection heating.

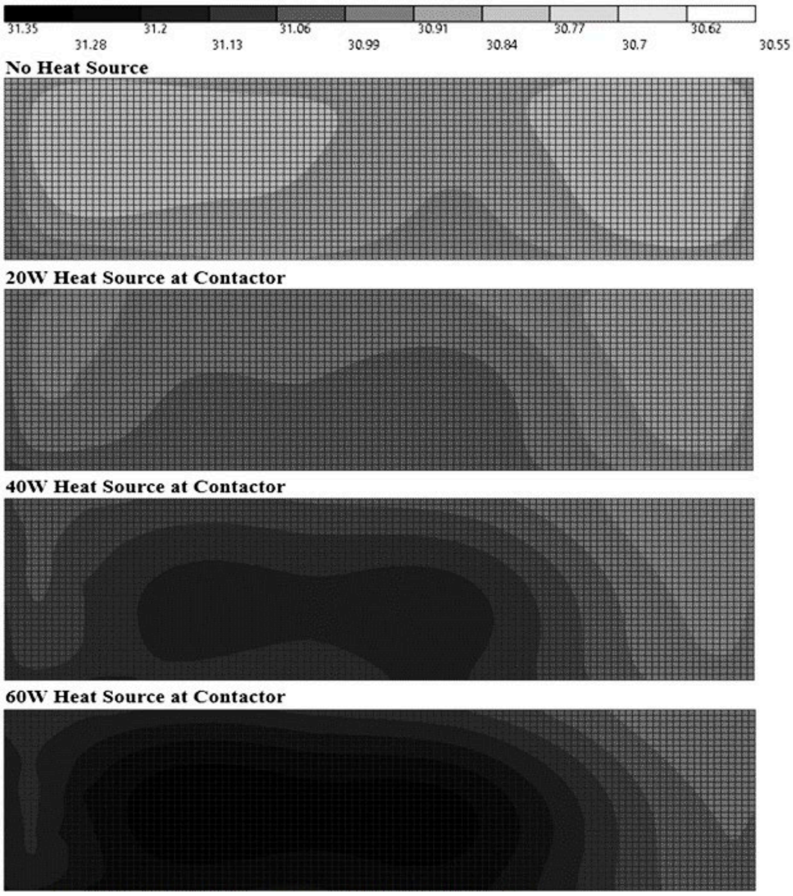

Figure 4 Surface temperature results for variations of contactor heat source load

The FLIR TG267 thermal sensitivity is 0.07 ºC, which is the smallest difference in surface temperature detectable by the device (FLIR, 2019). This sensitivity is commensurate with detecting anomalies before equipment failure occurs. Within ANSYS, temperature results are formed from individual temperature nodes which make up the overall distribution across the surface. To verify the visual changes apparent in the Figure 4 results would be detectable, the change in temperature at each node across the distributions was taken when compared to the associated node value at baseline. This data was analysed with the results shown in Table 2.

Surface ΔT from Baseline	**High Resistance Connection Location**					
	Contactor			*Rear Lug*		
	20W	*40W*	*60W*	*20W*	*40W*	*60W*
Mean (ºC)	0.157	0.321	0.487	0.042	0.092	0.153
Minimum (ºC)	0.046	0.094	0.143	0.008	0.017	0.027
Maximum (ºC)	0.241	0.486	0.736	0.087	0.198	0.342
Nodes above 0.07ºC (%)	95.55	100	100	15.69	52.66	83.64

Table 2 Model material setup data

For the contactor location, it is evident that all the mean surface ΔT data are above the 0.07 ºC temperature sensitivity. Further, the maximum surface ΔT observed was significantly larger than the camera temperature sensitivity. For the 20W heat source, the minimum ΔT seen was lower than 0.07 ºC, however, the vast majority (95.55%) of the surface exhibited a detectable temperature change. The analysis indicates that the ESIRT technique may be capable of detecting high resistance connection failure modes of 200, 400 and 600mΩ at the contactor location for the 37kW DOL starter module.

For the rear lug location, only the 40 and 60W heat source results provided mean surface ΔT data above the 0.07 ºC temperature sensitivity. However, the maximum surface ΔT observed was larger than the sensitivity for all heat sources. Unlike the contactor location, all heat sources demonstrated minimum ΔT values below the camera sensitivity, with far lower percentages of surface area shown to have detectable temperature changes. The analysis indicates that the ESIRT technique may be capable of detecting high resistance connection failure modes of 200, 400 and 600mΩ at the rear lug location for the 37kW DOL starter module. However, the data indicates location has a notable impact on the capability of ESIRT, with high resistance connections at the rear of the enclosure producing a significantly lower surface ΔT.

4. Conclusions and Future Work

The FEA analysis results demonstrate ESIRT can theoretically detect changes in surface temperature from a high resistance connection within the 37kW DOL starter module. However, location has a notable impact on the detection by ESIRT, with rear enclosure heating producing significantly lower surface temperature changes. FEA and CFD coupled analysis and experimental investigation must be conducted for comparison and validation of the FEA findings to enable definitive investigative conclusions to be reached regarding ESIRT efficacy.

Future works will see an investigation into ESIRT with higher specification IRT cameras applied across different sized enclosures and ambient temperatures. With the aim to establish an understanding of the influence of enclosure size, changes in external ambient air temperature, and IRT camera specifications have on the efficacy of ESIRT.

5. Acknowledgements

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6. References

Bagavathiappan, S., Lahiri, B. B., Saravanan, T., Philip, J., & Jayakumar, T. (2013). Infrared thermography for condition monitoring - A review. Infrared Physics & Technology, 60, 35-55 https://doi.org/10.1016/j.infrared.2013.03.006

FLIR. (2019). *TG267 Datasheet.* https://flir.netx.net/file/asset/21242/original/attachment

Popa, I. C., Dolan, A., Ghindeanu, D., & Boltaşu, C. (2014, 29-31 May 2014). Thermal modeling and experimental validation of an encapsulated busbars system. 2014 18th International Symposium on Electrical Apparatus and Technologies (SIELA)

Safe Work Australia (2012). MANAGING ELECTRICAL RISKS IN THE WORKPLACE.

Szulborski, M., Łapczyński, S., & Kolimas, Ł. (2021). Thermal Analysis of Heat Distribution in Busbars during Rated Current Flow in Low-Voltage Industrial Switchgear. Energies, 14(9), 2427. https://www.mdpi.com/1996-1073/14/9/2427

TEGG. (2015). *Infrared Inspections on Electric Panels without Removing Covers: Can the Inspection be Completed Correctly?* . TEGG Corporation.

Transmetra. (2021). TABLE OF EMISSIVITY OF VARIOUS SURFACES. https://www.transmetra.ch/images/transmetra_pdf/publikationen_literatur/pyrometrie-thermografie/emissivity_table.pdf

Usamentiaga, R., Pablo, V., Guerediaga, J., Vega, L., Molleda, J., & Bulnes, F. (2014). Infrared Thermography for Temperature Measurement and Non-Destructive Testing. Sensors (Basel, Switzerland), 14, 12305-12348. https://doi.org/10.3390/s140712305