# Distribution Transformer Monitoring Device

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**Abstract**

*In the summer of 2003/2004 there were a large number of failures of distribution transformers within Western Australia. One of the reasons that led to these failures was the absence of a monitoring system at the distribution level in Western Power's network. In 2005 Yuting Leong began developing a device that would monitor overload conditions of a distribution level transformer. The purpose of this project is to assess Yuting Leong's project and to develop, enhance and test a practical and cost effective transformer condition monitoring device. This project will be concentrating on cost analysis and reducing the cost of this device, improving and verifying the models used, as well as implementing and testing this device in the field.*

## 1.0 Introduction

Electrical subsystems around the world can generally be divided into three main sections; Generation, Transmission and Distribution. Electricity distribution is the final stage in the electrical subsystem, which supplies power directly to the consumer. Distribution transformers are devices in the distribution network that 'steps-down' the primary voltage to a secondary voltage which supplies consumers such as households directly. Distribution networks tend to have a radial configuration. [1] This means that if a fault were to occur at a distribution transformer the customers would experience an immediate loss of power.

At the moment there are no large scale online monitoring devices installed in Western Australia's electricity distribution network. The main reasons for this are due to vast numbers of distribution transformers in the network and their relatively low cost, which makes all the existing monitoring devices on the market not economically feasible. [2] The main objective of this project is to design and implement a real time, cost-effective online monitoring device that will observe and send an alarm to Western Power in the event of an upcoming and/or present overload conditions in the monitored distribution transformer.

## 1.1 Motivation

The motivation for this project began in the summer of 2003/04, where over 50 distribution transformers experienced faults leading to serious levels of distribution network problems. There were several reasons that led to these high number of faults, such as the lack of an online monitoring device as already mentioned in the previous section. Not only are overload conditions in distribution transformers not being monitored but the loading of each distribution transformer is not being recorded and remains unknown, making network planning difficult to perform. Currently, failures in the distribution network are only realised by customer notification. [2]

A study in Queensland showed that large parts of Queensland's power distribution network was built before World War II and only have a 40-50 year working life. [3] There is also the fact that the majority of distribution transformers directly feed power to end-users and rarely have inbuilt network redundancy. With the power network in Australia experiencing an aging distribution network, as well as any failure of a distribution transformer directly causing end-users to lose power, Western Power had identified that the ability to monitor distribution transformers would greatly improve the quality and reliability of the distribution network which will reduce the number of failures in the distribution network. [2]

## 1.2 History

The initial purpose of Leong's (2005) project was to develop a device that would monitor the conditions of the transformer in real-time, and trigger an alarm if an overload condition was reached or forecasted. Leong's prototype (hereon referred to as the 'original prototype') had the following objectives:

- The device is to be low cost
- Provide real time online monitoring and alarming
- The device must be able to be fitted without any transformer down time

At the end of 2005, a prototype was developed that would generally meet the above requirements. The original prototype used an Atmel microcontroller that was able to take readings from a temperature sensor and current transformer and communicate with Western Power through the use of a CDMA modem. The original prototype did not take many practical issues into account;

- The original prototype did not reach the stage of being implemented in an actual distribution transformer.
- The original prototype was not cost effective.
- A cost analysis was not conducted.

## 2.0 Objectives

The overall objective of this project is to reassess the original prototype and to develop a device with the following objectives:

- To attempt to reduce the overall cost of the device by sourcing alternative parts.
- Business case analysis – conduct a financially-based study to determine suitability/benefit of device vs. cost of not proceeding with device.
- To redesign the circuit in order to make the overall device more cost-effective and practical.
- To improve load and temperature forecasting models.
- To compare the new IEC60076.7 thermal model with the pervious model used in the prototype, and determine which model best calculates the actual transformer top oil temperature.
- To improve the overall code by adding increased functionality and practicality of the device.

## 3.0 IEC Thermal Model

There are two forms of overload conditions, excess current and excess temperature. Short term emergency loading are specified as the distribution transformer exceeding either 2 times the rated current, 115°C for transformer top oil temperature or 140°C for transformer hotspot temperature. One of the original requirements of the project was that the device must be fitted without any transformer downtime. This restriction makes it difficult to determine whether a transformer is overloaded in terms of temperature because both top oil and hot spot temperatures can only be directly measured inside the transformer. The ability to accurately measure or approximate the internal temperatures of the distribution transformer must be utilised in order for this device to work effectively.

The original prototype used a mathematical model from the AS 2374.7-1997 Australian standards to approximate the internal top-oil and hot-spot temperatures using two inputs, ambient temperature and current, both of which can be measured remotely from the distribution transformer. According to Leong (2005) this model was never verified in 2005. Recent testing confirmed that the top-oil temperature estimated using the original model deviated from the actual top-oil temperatures by around 10% on average.

The International Electrotechnical Commissions (IEC) released a draft of the international standard 'IEC 60076-7 Ed.1' in late 2005. This document proposed two new mathematical models to approximate the internal temperatures of a range of transformers using the load and ambient temperature inputs, similar to the model used in the original prototype. The two proposed models are the 'exponential equations solution' and the 'differential equations solutions'. As stated in the IEC 60076-7 document, quote "exponentials (equations) is particularly suited to determination of the heat-transfer parameters by test and for simplified scenarios". [4] The document also states that quote "...it (added complexity of differential equation solution) is also negligible for distribution transformers".[4] Since only a simple model needs to be implemented to calculate the internal temperatures on an hourly basis, it would be unneccessary and overly complex to implement the differential equation solution, and thus the exponential equation solution was chosen.

The exponential equation solution is described below. The hot-spot temperature due to a load factor increase is given by:

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \times \left[ \frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} \times f_1(t) + \Delta\theta_{hi} + \left\{ Hg_r K^y - \Delta\theta_{hi} \right\} \times f_2(t)$$

The hot-spot temperature due to a load factor decrease is given by:

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \times \left[ \frac{1 + R \times K^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \times \left[ \frac{1 + R \times K^2}{1 + R} \right]^x \right\} \times f_3(t) + Hg_r K^y$$

Where $f_1(t)$, $f_2(t)$, $f_3(t)$ are calculated as:

$$f_1(t) = \left(1 - e^{(-t)/(k11 \times \tau 0)}\right)$$
$$f_2(t) = k_{21} \times \left(1 - e^{(-t)/(k22 \times \tau w)}\right) - (k_{21} - 1) \times (1 - e^{(-t)/(\tau 0 / k22)})$$
$$f_3(t) = \left(e^{(-t)/(k11 \times \tau 0)}\right)$$

See IEC 60076 – 7 for definitions of variables. [4] This new thermal model proved to be more accurate than the model implemented in the orignal prototype. Figure 1 below shows the calculated top-oil temperatures compared to the actual top-oil temperatures.

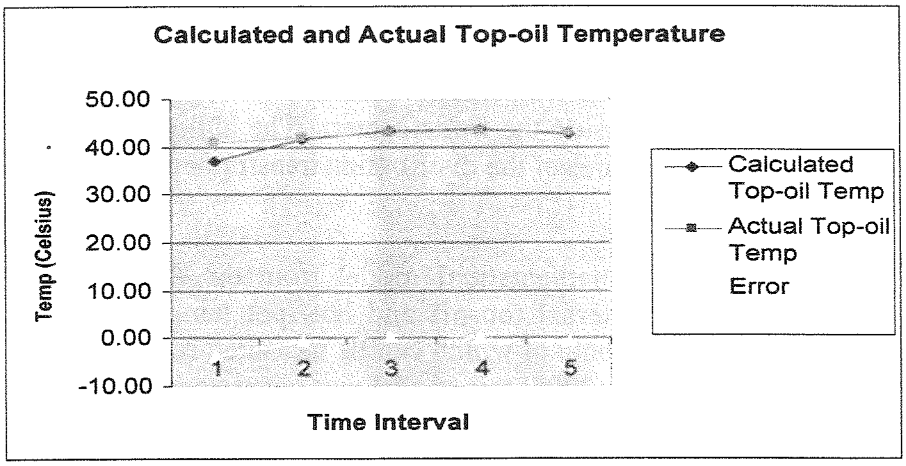


**Figure 1: Graph of calculated top-oil temperature using IEC Thermal modem and actual top-oil temperature**

## 4.0 Forecasting Model

As stated in the previous section, the IEC thermal model requires two inputs to approximate the top oil and hot spot temperatures within the distribution transformer, ambient temperature and load. If an overload situation was detected using current load and ambient temperature figures, by the time a Western Power personnel arrived at the transformer to conduct work on the transformer it may have already suffered serious damage. Therefore this device would be more effective if it were able to accurately forecast the short-term top oil and hot spot temperatures. This would require being able to forecast the future short-term ambient temperature and load. The original prototype already contained this functionality, and used a basic time of day linear model to forecast load and a modified sine wave model to forecast ambient temperature.

Overall these forecasting models were reasonably accurate, but as suggested in Leong (2005) quote "this device should look at improving the forecasting models, and implementing other, simpler and more accurate models". [2] It was decided that a mathematical model know as the 'Artificial Neural Network' (ANN) would be investigated to provide a more accurate forecasting model. ANN models can be used for both load and ambient temperature forecasting. One disadvantage of ANNs are that they are significantly more complex than the original models, but because the microcontroller would only need to compute these forecasts once every hour this added complexity should not hinder the device.

An ANN model is basically a group of neurons or elements that uses a mathematical model to process information. It is a non-linear modelling tool, and was originally inspired by the central nervous system and 'neurons'. [5] ANN models contain a self-learning capability which is able to 'detect and learn' patterns between a set of inputs and outputs. A diagrammatical representation of an ANN is shown in figure 2 below.

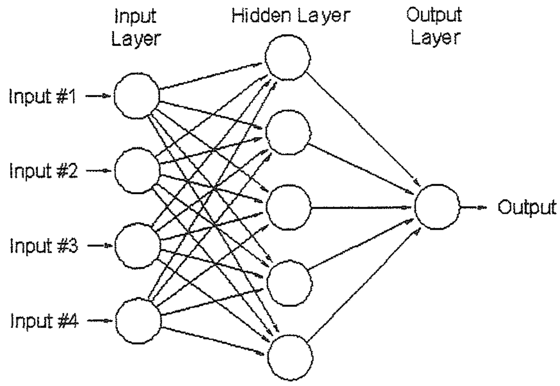


**Figure 2 - Diagrammatical representation of a feed-forward forward ANN [6]**

## 4.1 Forecasting Ambient Temperature

ANN models are highly customisable, as there are a lot of variations of mathematical models that can be used as well as input and output data used to train the network. However due to the limitations of the microcontroller many of these options are not feasible. After considerable research, it was concluded that the best choice of inputs to train the neural network is a batch training method using 7 input sets of 7 days, each input set containing 7 hours of data from the current time. After each hour, the input sets are updated and the neural network is run again to forecast the short-term ambient temperature. Figure 2 below shows an example of the ANN model when used to forecast the hourly temperatures 3 hours in the future over a span of 2 weeks in the month of January in 2005. Note that this period is one of the hottest periods of the year and thus the accuracy of the forecasting model for this period would be of greater benefit for this project as historically distribution transformers tend to have a higher fail rate in the summer period. [7]

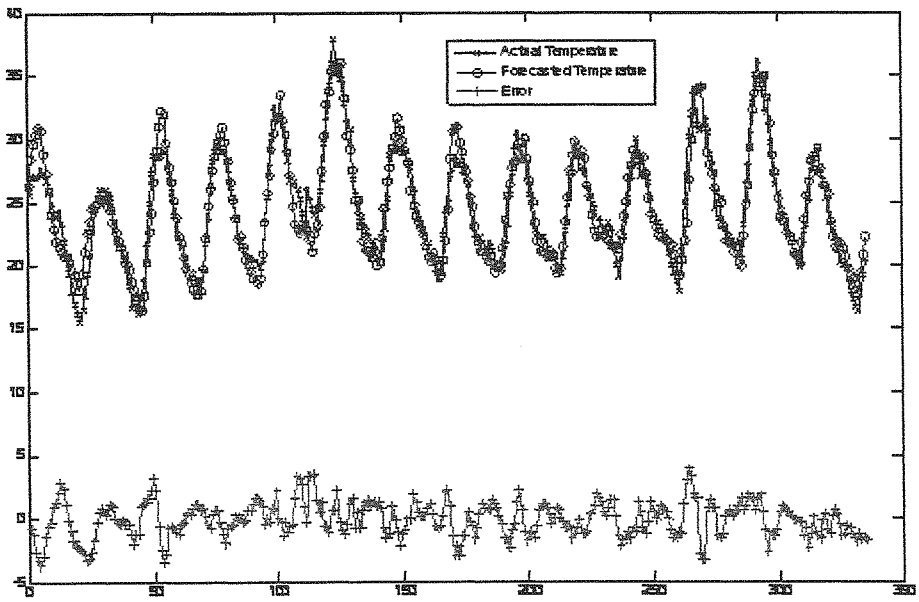

**Figure 3 – ANN Model forecasting Temperature 3 hours in future – Jan 2005**

The ANN model is a significant improvement over the modified sine curve model used in the original prototype. Table 1 compares the forecasting results of the ANN model against the original modified sine curve model for the same two week period in January 2005.

| | Max Error (°C) | Max Error % | Mean Error (°C) | Mean Error % |
|---|---|---|---|---|
| ANN Model | 3.8634 | 19.31% | 1.1178 | 4.65% |
| Modified Sine Curve | 7.8355 | 28.8% | 2.5674 | 9.93% |

**Table 1 – Comparison of modified sine curve model and ANN model**

These results show that the ANN is an improvement over the modified sine curve model by approximately 50% in absolute terms.

## 5.0 Device

The original prototype device produced in 2005 contained the ability to detect an overload situation and send a warning through an SMS. It was tested on a 'development board' which is convenient for testing but not feasible for implementation and production. The purpose of this project is to identify all the practical long-term issues and cost issues concerning this device, solve them and attempt to implement a prototype in the field. A simple block diagram representation of the current device is shown below in figure 4.

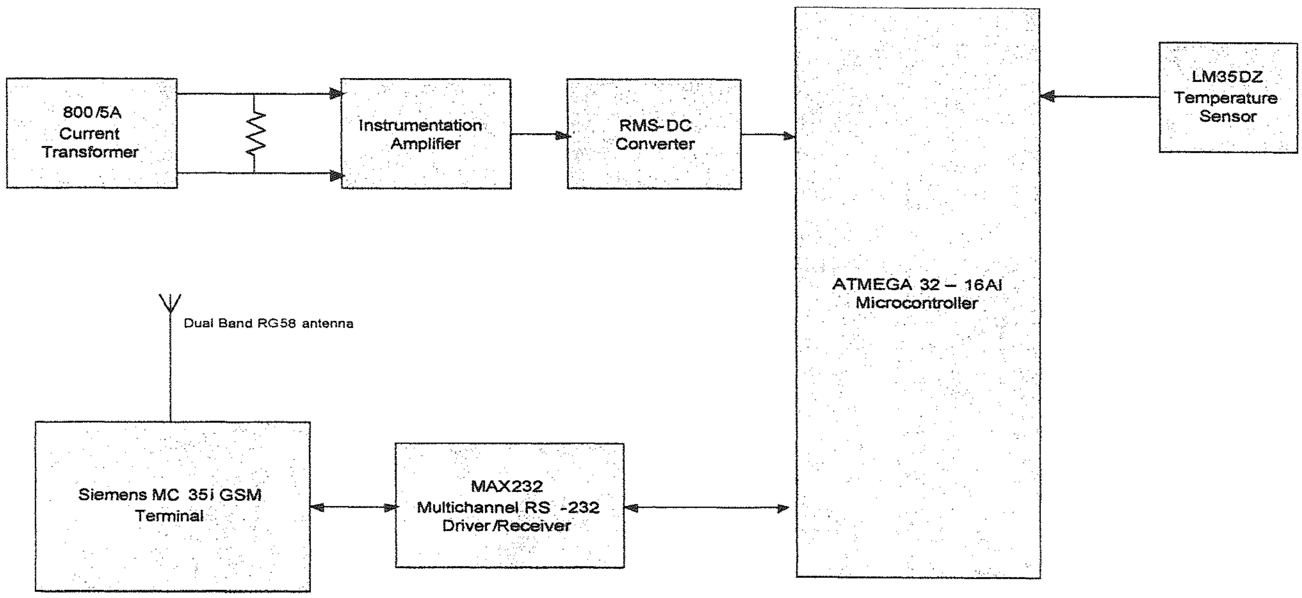


**Figure 4 – Block Diagram Representation of the Circuit Diagram**

## 5.1 Cost

The cost of the original prototype (equipment only) cost $1266.93. [2] The most expensive parts of the original prototype was the CDMA modem, the current transformer and the current transducer. These three parts were chosen because they were Western Power standard devices. [2] If these three parts were replaced with cheaper alternatives, it would significantly improve the overall cost-effectiveness of the device.

The original prototype device utilised a CDMA modem. It was decided that this should be replaced with a Siemens MC35i GSM Terminal. One of reasons is that it is significantly cheaper than the CDMA modem. Another reason is that in November 2005 it was announced that

Telstra would be phasing out their CDMA network by 2009. This would definitely have a direct negative implication on this device if a CDMA modem were chosen.

The current transformer in the original prototype can be directly replaced with a cheaper current transformer. With the current transducer, it was decided to look into the idea of completely designing a circuit that will perform the equivalent function of the current transducer, which is to convert an AC current to a DC voltage. The device consisted of an instrumentation amplifier and an RMS-to-DC converter integrated controller. Table 2 below shows the results and the percentage error of the circuit.

| Actual Current | Expected Current | % Error |
|---|---|---|
| 200 | 200 | 0.00% |
| 308 | 300 | 2.67% |
| 412 | 400 | 3.00% |

**Table 2 – Comparison of Actual and Expected Current of the 'Current Transducer' circuit**

By replacing the current transformer with a cheaper alternative (with similar accuracy) and designing a circuit which included the use of an instrumentation amplifier and a RMS-DC converter to replicate the current transducer, the cost of the current transformer and transducer was reduced by approximately 58%.

## 5.2 Code

The original prototype was able to process the load and temperature readings, and calculate if any overload conditions have been reached. Apart from this, the original prototype did not incorporate a lot of practical issues with installing this device in the field. For example, in the case that the source of power to the device was temporarily disconnected, the time on the microcontroller would be reset. The original device did not have any functionality in place that could set the clock to its correct time. Below are several of many issues concerning the lack of functionality of the original prototype, and how they were overcome.

### 5.2.1 Remote Setup Function

The original prototype did not include any functionality that allowed personnel to remotely set up the device. All variables such as the IEC thermal model constants (see section 3 above) and the time would have to be hardcoded during the production/assembly stage which would be very difficult and costly to set up. Being able to remotely set up these variables remotely would improve the practicality of this device by making it easier and cheaper to set up.

This remote function is done by sending an SMS into the modem, and the microcontroller will continually check if any SMSs are stored in the modem. Currently two remote commands have been implemented and tested; sending IEC thermal constants and the time.

### 5.2.2 Data Acquisition Capability

The original prototype's main function was to determine whether an overload condition had or is forecasted to occur. It will improve the overall value and functionality of the device if it were able to conduct a second main function of logging temperature and load data and sending the information to Western Power periodically. This function has many advantages, such as Western Power being able to determine whether the distribution transformer is close to being heavily overloaded, and giving them the ability to conduct network planning more efficiently.

## 6.0 Conclusion

This paper has briefly outlined the background, objectives and results of a prototype of a distribution transformer monitoring device. Overall the results were highly successful because it demonstrated the feasibility of a low cost transformer monitoring device of reasonable accuracy. Many improvements were made since the original prototype, such as the accuracy of the forecasting models and the implementation of a number of practical functions as described above. The implementation of this device can help to identify overloading transformers and provide load and temperature data, and thus assist in network planning and improving the reliability of the distribution network.

## 7.0 References

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