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Flexible Networks
for a Low Carbon Future

Enhanced Transformer Ratings Tool

- A Design and Planning Application Guide

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Executive Summary

To facilitate a future flexible network, it is critical to develop improved network planning and operations tools and practices that can provide a greater understanding of network behaviour and enable a more appropriate techno-economic response to load growth. Network monitoring data has traditionally been deployed and analysed consistent with a fit and forget network below 33kV. This will be inadequate as increasing amounts of low carbon technology including PV, electric vehicles, heat pumps and energy storage connect to the distribution network and with the growth of demand side response and generation ancillary services.

Primary transformer ratings are typically based on the nameplate rating i.e. an ambient temperature of 20°C and an insulation temperature of 98°C. TNEI Services Ltd and The University of Strathclyde have developed a software tool which calculates enhanced/dynamic thermal ratings for primary transformers. This is based on an industry standard IEC thermal model. The use of enhanced seasonal thermal ratings that leverage the interdependencies of ambient temperature and high load should help to release additional capacity from the network, enabling load related reinforcement to be deferred. The acceptable transformer insulation temperature under contingency conditions can also be reviewed and increased to gain capacity with minimal impact on aging.

A Microsoft Excel-based software tool has been developed which contains linkages with key power flow data and asset databases. Enhanced seasonal ratings are calculated for winter, summer and spring/autumn based on historic load profiles, seasonal ambient temperatures, insulation temperature and transformer size and cooling details. Enhanced ratings can then be exported to the network operations SCADA software and power systems software used by network planners. It is also possible to calculate an enhanced dynamic rating for use in maintenance outage planning or cyclic ratings in the event of an unplanned outage. The transformer aging rate associated with the enhanced rating is also calculated.

New seasonal firm capacities were calculated for the three Flexible Networks trial sites based on an insulation temperature of 110°C. Capacity headroom gains of between 10% and 20% were possible in winter peak loading periods with minimal impact on aging.

A cost-benefit analysis case study undertaken for St Andrews found that replacement of two primary transformers, giving an increase of 19 MVA, would cost in the order of £32k/MVA whereas, deployment of monitoring to support the use of enhanced thermal ratings would cost approximately £4.5k/MVA, a significant cost saving.

Extensive stakeholder engagement was carried out with SPEN staff throughout the course of software development and from this, recommendations are provided for next steps towards future integration into business-as-usual. These include;

- Further automation, such as annual calculation of enhanced ratings and uploading to power systems software.
- Improved monitoring by increasing number of weather stations or top oil temperature recording for key primary transformers.

- Increased storage and accessibility of transformer information in business databases.

CONTENTS

Glossary

BSP	Bulk Supply Point (Primary substation)
CER	Continuous emergency rating
CMR	Continuous maximum rating
FCO	First Circuit Outage
GE Poweron	Network Operations control software
GSP	Grid Supply Point (supply point from National Grid to DNOs)
LCNF	Low Carbon Network Fund
LTDS	Long Term Development Statement
OD	Oil Directed
OF	Oil Forced
ONAF	Oil Natural Air Forced
ONAN	Oil Natural Air Natural
PI	Process Instrumentation – SPEN's Network Monitoring Data Historian System
SCO	Second Circuit Outage
SPD	Scottish Power Distribution
SPEN	Scottish Power Energy Networks (incorporating SPM and SPD)
SPM	Scottish Power Manweb

1 Introduction

1.1 Background on Flexible Networks

‘Flexible Networks for a Low Carbon Future’ is a Scottish Power Energy Networks (SPEN) Tier 2 Low Carbon Network Fund (LCNF) trial project. LCNF Tier 2 projects are awarded annually on a competitive basis to UK Distribution Network Operators (DNO) and are administered through Ofgem.

Flexible Networks will provide the DNOs with economic, DNO-led solutions to enhance the capability of the networks as heat and transport are increasingly de-carbonised resulting in an increase in electricity use. Crucially, these solutions will be capable of being quickly implemented and will help to ensure that the networks do not impede the transition to a low carbon future.

Development of the Enhanced Transformer Ratings Tool and associated Application Guide has been led by TNEI Services (TNEI) and University of Strathclyde with guidance from SPEN. The underlying transformer thermal model was initially developed by The University of Strathclyde as part of an undergraduate dissertation project. This has been further developed to produce a software tool for calculating enhanced ratings for transformers.

1.2 Business Need

At present, transformers are run on a fixed nameplate rating throughout the year. Network capacity is calculated from these asset ratings and compared to the network demand during annual network review. However, the use of fixed asset ratings does not fully consider the actual thermal conditions experienced and can lead to unnecessary triggering of network reinforcements and corrective measures to reduce load due to indications that thermal headroom is exhausted.

By taking advantage of the interdependencies of seasonal temperature change, load profiles and relative aging, there is potential to unlock additional network capacity which could allow reinforcement to be deferred. Peak demand generally occurs in December when ambient temperature is lowest, which will enhance the asset thermal rating and thus, should provide additional capacity when it is required most.

The innovations being trialled as part of Flexible Networks including dynamic thermal ratings, will test whether theoretical benefits can be achieved in practice, and to establish timescales, costs and any challenges to integration into business-as-usual.

This report explores the use of enhanced thermal ratings to improve the thermal management of transformers, identify capacity headroom and to understand and manage the potential impacts on distribution system operation and design. This should ultimately delay network reinforcement and enable more efficient network investment. The development of a methodology and software tool to calculate enhanced asset ratings will form part of a new thermal management system.

1.3 Enhanced Transformer Ratings Tool

1.3.1 Current Primary Transformer Rating Approach

SPEN consists of two geographical licence areas; Scottish Power Manweb (SPM) and Scottish Power Distribution (SPD). These two licence areas have quite different distribution network designs and network planning and operational policy and practice reflects this as detailed below.

SPM

The SPM network is designed and operated in a meshed configuration with primary transformers typically run as part of a group of up to five transformers. In more rural areas, HV networks are run in single transformer groups with interconnection to adjacent networks during contingency conditions.

There are several transformer sizes used in the HV network. Primary transformer application and rating policy (TRAN-01-004) states that ONAN transformers can have a generic cyclic overload applied to them which allows up to a 130% overload for 3 hours. However, for the remaining hours, out of a 24 hour period (21), the transformer must run at 80% or less of the nameplate rating to allow the transformer to cool down. ONAN/ONAF transformers do not have any overload capability and are operated at nameplate rating.

SPD

The SPD network is designed and operated radially with HV network groups generally run as two parallel transformers, connected via a bus section circuit breaker. During a contingency condition, the load transfers to the remaining transformer. Transformers in SPD have either an ONAN/ONAF or ONAN/ONAF/Continuous emergency rating (CER). CER ratings are typically double the ONAN rating and can be run continuously however with that does come significant aging. More information on CER ratings can be found in section 2.4.2.

1.3.2 Improved Primary Transformer Rating Approach

An improved approach to the calculation of transformer ratings would take advantage of the following key interdependencies with the aim of increasing network group capacity:

- Correlation of low ambient temperature e.g. high load in winter (see Appendix B for correlation at Flexible Network trial sites, please note that St Andrews weather data measured over a full year was not available due to monitor issues).
- Use of actual transformer loading profiles (compared to simple “top-hat” profiles) to calculate thermal heating and cooling.
- Short-term increase in acceptable transformer insulation temperature resulting in only minimal impact on transformer aging due to increased aging only occurring during infrequent contingency conditions.
- Transformer failure usually attributable to mechanical aging.

HV network groups typically fall within P2/6 network Class C (maximum demand between 12MW and 60MW), where;

- First Circuit Outage (FCO) results in no loss of supply
- Second Circuit Outage (SCO) may result in 100% loss of supply

Thus, network firm capacity is based on a summation of transformer ratings within the network group, to comply with network security for FCO. For example, for a network group of three 10MVA transformers, the firm capacity would be 20MVA. It is anticipated that the enhanced ratings will be used to then calculate new HV group firm capacities.

1.3.3 Envisaged Integration with Business Functions

It is envisaged that the enhanced transformer seasonal ratings will be calculated on an annual basis for each transformer within a specific network group. This would enable calculation of a new HV network group firm capacity by Network Planning. A view on an acceptable short-term transformer insulation temperature will be developed following wider analysis of the primary transformer asset base and verification with experimental measurements. This should recognise uncertainties associated with ambient temperature and load measurements.

The methodology incorporates the use of real ambient temperature and load data. Measured top oil temperature could also be incorporated in future, if available. Limited calibration of Liverpool Road primary transformer thermal parameters suggests that the IEC 60076-7 example thermal parameters for calculating top oil and hot spot temperature are conservative. Thus, including top oil temperature measurements and/or specific transformer thermal parameters will improve model accuracy.

Assessment of a transformer thermal rating over a specific planned outage period (based on historical or forecast ambient temperature and load data) will assist Network Operations in optimising network configuration plans and response to contingency. The ability to calculate a transformer dynamic rating for a shorter period e.g. several hours while the network is reconfigured, during an unplanned outage is also seen as a valuable tool for control engineers.

1.3.4 Assessment of Transformer Suitability for Enhanced Thermal Rating

DNV GL performed detailed analysis on the three Flexible Networks trial sites to evaluate the potential for applying dynamic thermal ratings to the primary transformers and to characterise the aging associated with existing and future load patterns. This included;

- Initial site suitability studies
- Calculation of future load patterns and characterisation of associated transformer aging, based on actual load patterns:
    - Actual load pattern increased by 8%, 10% and 12%
    - Actual load pattern increased to a peak load of 21 MVA

    - 21 MVA load pattern increased by 8%, 10% and 12% (for St Andrews)
- Creating future load patterns and calculating transformer aging, based on actual load patterns and different levels of load increase due to:
    - Charging of electrical vehicles
    - Installation of electrical heating.

Key findings from the analysis were that all the primary transformers within the trial sites are thermally low loaded and could potentially be loaded above nameplate rating without increasing the loss of life significantly. The analysis performed by DNV GL focussed on transformer suitability and characterising aging based on annual load profiles, while the analysis tool described in this Application Guide more specifically considers enhanced ratings (and associated aging) under contingency conditions.

2 Transformer Thermal Modelling

2.1 Transformer Thermal Models

The transformer thermal model presented in IEC 60076-7 is well established within the power systems industry and widely used. There are other thermal models available however these tend to be significantly more complex, requiring inputs which are not readily available and introduce uncertainty. The Enhanced Transformer Rating Tool is based on the IEC model.

2.2 IEC 60076-7 Thermal Model

The IEC model contains a set of differential equations which are used to calculate the winding hot spot temperature. The hot spot temperature is defined at the hottest part of the transformer windings and it is this temperature that the insulation must withstand. Although most of the insulation within the transformer will be at a lower temperature, the hot spot temperature is critical as only one point of failure in the insulation is required for the entire asset to fail. Figure 2-1 shows the block diagram of the thermal model presented in IEC 60076-7.

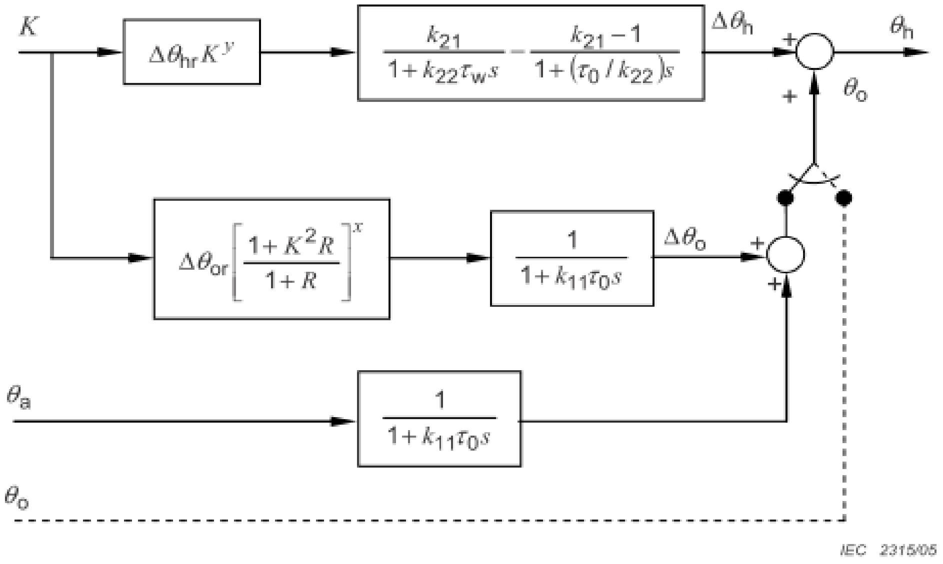


Figure 10 – Block diagram representation of the differential equations

Figure 2-1 IEC Block Diagram [1]

The IEC thermal model parameters shown in Figure 2-1 are as follows:

- **K** – Load factor. Ratio between the load current and rated nameplate current (at continuous maximum rating).
- **Θa** – Ambient temperature around the transformer.
- **Θo** – Transformer top oil temperature.

- **S** – Laplace operator
- **Δθor** – Steady state top oil rise above ambient temperature at rated losses.
- **Δθo** – Top oil temperature rise at load considered.
- **Δθhr** – Hotspot temperature gradient at rated current.
- **Δθh** – Hot spot to top oil gradient at load considered.
- **Θh** – Hot spot temperature
- **τo** – Oil time constant.
- **τw -** Winding time constant.
- **R** – Ratio of load losses at rated current to no load losses.
- **x** – Oil exponent, describing the relationship between total losses and top oil temperature rise.
- **y** – Winding exponent, describing the relationship between current and winding temperature rise.
- **k11, k21 & k22** – Model constants describing the temporal behaviour of the transformer.
- **Δt** – This is interpolation time step used by the model.

The IEC thermal model inputs and outputs are summarised below.

Model inputs:

- Load factor (K)
- Ambient air temperature (Θa**)**
- Transformer top oil temperature (Θo**)**
- IEC model parameters (Δθor, Δθhr, τo, τw, R, x, y, k11, k21 & k22)

Model outputs:

- Maximum hot spot temperature (Θh**)**

As can be seen from Figure 2-1, the top oil temperature component of the model is shown as dashed. This is because top oil temperature is not typically measured for transformers and so ambient temperature is used to characterise temperature instead. If top oil temperature was measured, ambient temperature along with input parameters Δθor, R, X and K11 would not be required. This should improve the accuracy of the thermal model.

Examples of values for the IEC model input parameters can be found within IEC 60076-7 and are shown below in Figure 2-2. Values for distribution transformers (up to 2.5MVA) and medium and large power transformers (up to 100MVA and greater than 100MVA) are given. In addition, values for different transformer cooling type designations; Oil Natural Air Natural (ONAN), Oil Natural Air Forced (ONAF), Oil Forced (OF) and Oil Directed (OD) are also included.

IEC 60076-7 also provides input parameter values for different cooling types by restricted or non restricted oil flow. A restricted cooling type is defined as a transformer having radial spacers less then 3mm thick, in a disc winding with oil flow washers.

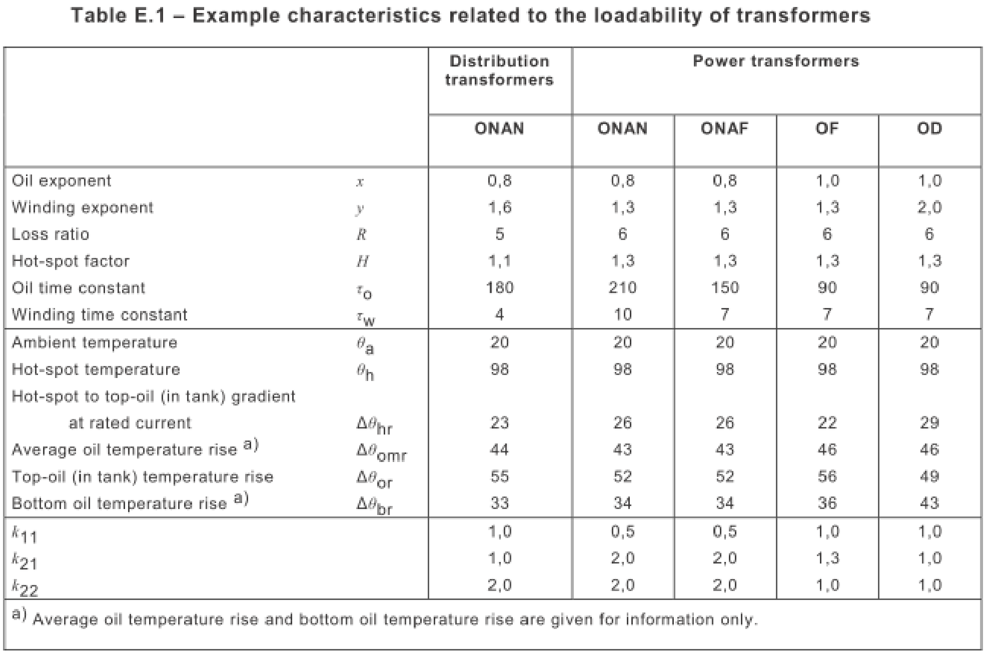


Table E.1 – Example characteristics related to the loadability of transformers

		Distribution transformers	Power transformers			
		ONAN	ONAN	ONAF	OF	OD
Oil exponent	x	0,8	0,8	0,8	1,0	1,0
Winding exponent	y	1,6	1,3	1,3	1,3	2,0
Loss ratio	R	5	6	6	6	6
Hot-spot factor	H	1,1	1,3	1,3	1,3	1,3
Oil time constant	τ_o	180	210	150	90	90
Winding time constant	τ_w	4	10	7	7	7
Ambient temperature	θ_a	20	20	20	20	20
Hot-spot temperature	θ_h	98	98	98	98	98
Hot-spot to top-oil (in tank) gradient at rated current	$\Delta\theta_{hr}$	23	26	26	22	29
Average oil temperature rise [a]	$\Delta\theta_{omr}$	44	43	43	46	46
Top-oil (in tank) temperature rise	$\Delta\theta_{or}$	55	52	52	56	49
Bottom oil temperature rise [a]	$\Delta\theta_{br}$	33	34	34	36	43
k_{11}		1,0	0,5	0,5	1,0	1,0
k_{21}		1,0	2,0	2,0	1,3	1,0
k_{22}		2,0	2,0	2,0	1,0	1,0

[a] Average oil temperature rise and bottom oil temperature rise are given for information only.

Figure 2-2 IEC 60076-7 example thermal model parameters [2]

Some of the parameters can be calculated on an individual transformer basis rather than using the recommended IEC values. This can help to improve the accuracy of the thermal model. Transformer heat run tests produce the required information. However, in practice, this type of test is often not performed on transformers or the test information has not been requested from the manufacturer or is no longer available.

2.3 IEC 60076-7 Insulation Aging

The insulation aging model in IEC 60076-7 is based solely on hot spot temperature. However, in reality other factors such as historical power flow through the transformer and oil quality also affect the insulation aging rate.

It is recommended that oil samples are taken routinely to monitor the presence of moisture, oxygen and acid within the oil and thus, the quality of the oil.

The rate of insulation aging can be calculated as per the following equation for non-thermally upgraded insulation: [3]

$$V = 2^{(\vartheta_h - 98)/6}$$

V = Insulation age rate

Θh = Insulation hot spot temperature

The following table, from IEC 60076-7, provides an indication of the effects of hot spot and thus insulation temperature on the age rate [4].

Table 2-1 IEC Hot Spot Vs Age Rate

Hot Spot Temperature Θh (°C)	Non-thermally upgraded insulation age rate V
80	0.125
86	0.25
92	0.5
98	**1**
104	2
110	4
116	8
122	16
128	32
134	64
140	128

2.4 Transformer Ratings

The thermal model can then be applied to calculate transformer ratings. Various primary ratings as currently used within SPEN are described below.

2.4.1 Continuous Maximum Rating

The continuous maximum rating (CMR) or nameplate rating as it is more commonly known is defined at an ambient temperature of 20°C and the continuous load that gives a hot spot temperature of 98°C. An ambient temperature of 20°C comes from the IEC standard and is given as the average yearly temperature. The hot spot temperature of 98°C is based on non-thermally upgraded insulation. At this hot spot temperature, the insulation will age at a rate of 1, or 24 hours of life lost over a 24 hour period of time. A transformer will last an estimated 15 years operating continuously at this rating however in reality the insulation temperature will usually be much lower due to network design for contingency conditions and because transformers start life with a relatively low load, with load increasing gradually. A typical stated lifespan of a transformer is often quoted by manufacturers as 40 years for nameplate rating. Usually transformers in the UK last longer than the quoted 40 years because ambient temperature is often below 20°C in the UK and due to load profile variation. For more information on CMR ratings refer to ENA TS 35-3.

2.4.2 Continuous Emergency Rating

Continuous emergency ratings are calculated at an ambient temperature of 5°C. This is based on winter temperatures as winter months typically experience the highest demand and transformers are most likely to be required to operate at an emergency rating in this case. Ratings are given in the following order - ONAN, ONAF (CMR) and CER. CER ratings are typically twice the ONAN rating. The insulation temperature associated with CER ratings is 140°C. At this temperature the insulation will be subject to rapid aging however it is anticipated that the transformer may only run at this temperature for several days/weeks over its total life. In practice, it is understood that transformer designers would use an insulation temperature of 120°C to allow for some uncertainty as a few degrees can make a significant difference to aging. For more information on CER ratings see ENA TS 35-2.

2.4.3 Cyclic Rating

A cyclic rating is a temporary rating above the CMR rating defined for a specified time period e.g. several hours, within a 24 hour period. Cyclic ratings are designed to allow a short-term overload due to an unplanned outage occurring such as asset failure. It is anticipated that within a few hours the fault will have been fixed or the load level will have reduced. Cyclic ratings can be calculated at any ambient temperature as an unplanned outage could occur at any time during the year. Cyclic ratings often use an insulation temperature of 160°C which according to IEC 60076-7 is a short term emergency rating value. However, transformer designers would typically not recommend use of such a high insulation temperature due to thermal loading uncertainty and associated risk.

2.4.4 SPEN Transformer Ratings

Table 2-2 shows the various SPEN transformer rating types. Transformer rating principles and details are given in “Specification for 33kV System Transformers” (TRAN-03-020),”Equipment Ratings and Assessment of EHV//HV Systems (ESDD-02-

007) and the Manweb Primary Transformer Application and Rating Policy (TRAN-01-004).

SPM do not employ CER ratings due to the meshed network configuration. This can be explained using the radial SPD network as an example. Consider a typical SPD HV network group of two transformers. If one transformer is out for maintenance or fails then the other transformer will take up the remaining load i.e. approximately double its previous load. CER ratings are typically double ONAN ratings, for this reason. With SPM, the load is distributed across up to five transformers so the required increase in load on these transformers during contingency or maintenance is much less.

Table 2-2 SPEN Primary transformer rating types

Network	**SPD**					**SPM**		
ONAN (MVA)	7.5	12	12	15	20	4	7.5	7.5
ONAF (MVA)	10	24	19	21	32	-	-	10
CMR (MVA)	10	24	19	21	32	4	7.5	10
CER (MVA)	-	-	24	-	40	-	10[‡]	-

[‡] Based on a cyclic rating, up to 3 hours

HV group firm capacities which are based on CER ratings will not gain additional capacity through the use of enhanced ratings as the CER rating is already at a maximum. Enhanced ratings for these transformers will likely be much lower due to not being based on a fixed ambient temperature of 5°C. SPM 7.5 MVA transformers, with retrofitted fans, could also result in lower firm capacities when using enhanced ratings. This is due to the current firm capacities being based on a 10 MVA (cyclic) rating.

3 Enhanced Transformer Ratings Tool Functionality

3.1 Functional Specification

3.1.1 General

The Enhanced Transformer Ratings Tool has been developed and implemented using Microsoft Excel and Visual Basic. MS Excel was chosen due to being in common use across industry and availability of support. The code within the tool has been written in a standard, easy to understand format for anyone with a coding background. This will facilitate future maintenance and enhancement modifications.

The tool has been designed to analyse primary transformers however, the IEC thermal model parameters can equally be used for transformers with ratings less than 7.5MVA and greater than 12MVA.

The IEC standard provides the same thermal model input parameters for medium power transformers and large power transformers. However, it is recommended that further investigation is carried out to confirm the suitability of the thermal model for use with large power transformers (>45MVA, i.e. grid transformers).

3.1.2 Seasonal Ratings

Basic inputs for this function are load profile for the highest loaded seasonal day, ambient temperature and transformer details (a full list of the required inputs are detailed in section 3.4). The IEC thermal model calculates an initial peak hot spot temperature from the load profile and ambient temperature. The load profile is then scaled up until the peak hot spot temperature reaches the specified temperature limit (98°C is standard however this can be modified by the user).

Three enhanced transformer ratings are calculated for winter, summer and spring/autumn based on three ambient temperatures and highest seasonal load profiles. It is envisaged that seasonal ratings would be calculated once a year for transformers in HV network groups identified as approaching firm capacity. Where opportunities exist to take advantage of enhanced seasonal thermal ratings to gain additional capacity headroom, the transformer ratings in PowerOn, and power systems modelling tools such as IPSA and DigSilent could be automatically updated. Network group firm capacity would also be updated in the LTDS.

Where there is a clear cost-benefit case, local weather monitoring and possibly top oil temperature monitoring could be installed to reduce modelling uncertainty and potentially increase enhanced seasonal ratings further.

Transformer aging is also calculated based on the new enhanced seasonal ratings. These are presented in terms of nameplate and enhanced ratings, to give an indication of how the new rating will impact transformer aging during contingency conditions.

3.1.3 Dynamic Rating

The dynamic ratings function is aimed at network operators planning for a maintenance outage. This function calculates a single enhanced thermal rating over a specified time period for example, a 2 week planned outage based on historical or forecast ambient temperature and load data. The inputs for this function are similar to the seasonal ratings function only instead of entering a seasonal date, a start and finish date is entered.

3.1.4 Cyclic Rating

The cyclic rating function is aimed at network operators who may need to calculate a short term enhanced thermal rating for a specified fault duration within a 24 hour period. The cyclic rating function requires the input of pre load, overload duration and transformer details. A pre load is applied for a period of 12 hours to increase transformer temperature. Then the load is scaled up for the required cyclic duration, until the maximum insulation temperature is reached. The load is then reduced to pre load value for the remaining time in the 24 hour period. Multiple pre loads and durations can be studied simultaneously. A range of cyclic rating load duration profiles are plotted as output. Figure 3-1 shows the load profile for a cyclic study, a flat load profile is assumed for cyclic rating calculations.

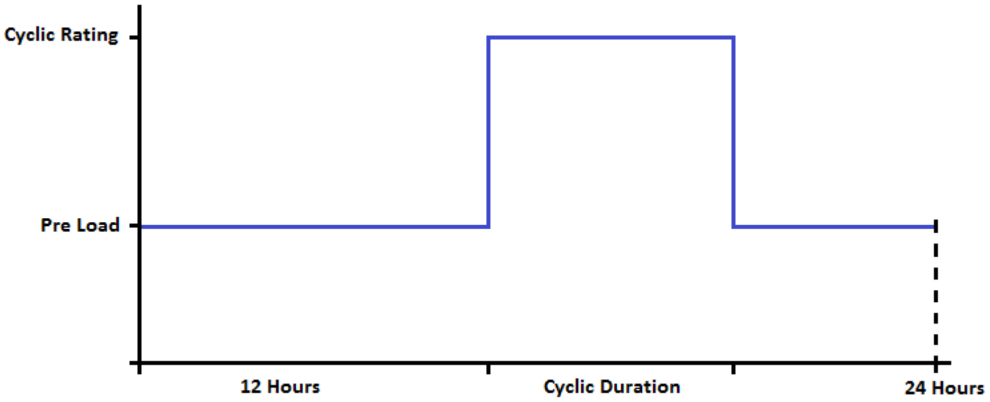


Figure 3-1 Cyclic Profile

3.2 Other Modelling Considerations

3.2.1 IEC Model Parameters

Standard parameters from IEC 60076-7 were used (see section 2.2) as it was not possible to source information on transformer thermal parameters from SPEN databases.

There was also no evidence that SPEN transformers have restricted oil flow although this is not conclusive. Such information is unlikely to be provided by a manufacturer for legacy transformers, if they are still in business. Determining the makeup of the windings and possible oil flow restriction by inspection would require the transformer to be taken apart and is therefore deemed unsuitable.

Further analysis should be undertaken as a sensitivity analysis to determine the effect of using thermal model parameters for a restricted oil flow transformer.

SPEN primary transformer continuous maximum ratings and corresponding cooling types for use in determining thermal model parameter values are tabulated below. Standard IEC thermal model parameters have been used and transformers have been assumed to not have oil flow restrictions.

Please note that SPM 7.5MVA ONAN/10MVA transformers with retrofitted fans should be treated as 7.5MVA units as there is no warranty provided for the 10MVA rating and it is considered to be cyclic only (see Manweb Primary Transformer Application and Rating Policy TRAN-01-004 Issue 1).

Table 3-1 SPEN primary transformer CMR and cooling type

CMR Rating (MVA)	Cooling Type
7	Primary, ONAN
6	Primary, ONAN
7.5	Primary, ONAN
10	Primary, ONAF
24	Primary, ONAF
40	Primary, ONAF

3.2.2 Modelling of Contingency Conditions

The firm capacity of the HV network group is based on individual aggregated transformer rating under contingency conditions. For a primary group, this contingency condition is a First Circuit Outage. For example, for a three transformer group of 10MVA ONAF rated transformers, the firm capacity will be 20MVA or (N-1) times the CMR rating.

Contingency scaling factors have been included in the tool to enable the input load profile to be scaled up to represent a contingency for both radial and meshed network configurations. This is done by means of a contingency scaling factors lookup table (see Table 3-2).

Table 3-2 Contingency Scaling Factors

No of Transformers in Network Group	N-0	N-1	N-2
1	1	1.5	2
2	1	2	2.5
>2	Tx Rating + [(Tx Rating * Contingency) / (No of Tx - Contingency)]		

The scaling factor depends on how many transformers are in the HV network group and the level of contingency. For groups containing more than 2 transformers, a formula is used to scale the load data equally between the remaining transformers. For groups of less than 3 transformers, fixed scaling factors are used to simulate load being shifted from two transformers to a single transformer or partial load transfer from a single transformer in an adjacent network group through feeder interconnections (back feeding). Note that for N-0 a scaling factor of 1 will be used i.e. no change in load.

Example: N-1, three 10 MVA transformers.

$$Contingency\ scaling\ factor = 10 + \left[\frac{10 * 1}{3 - 1}\right] = 15\ MVA$$

So if three transformers are loaded up to 10MVA each and one is lost due to outage, the remaining two transformers take up a total of 10MVA of load i.e. 5 MVA each to supply a total new load of 15 MVA.

For a group of 3 or more transformers, it has been assumed that the load pick up will be shared equally between the remaining transformers. In reality, the amount of load each transformer picks up will vary depending on the impedance of the network. To model this accurately a load flow study would be required.

3.2.3 Seasonal Ambient Temperatures

One of the key inputs into the thermal model is the ambient temperature. Average seasonal temperatures have been used although measured temperatures could also be used as input if available to better capture local weather characteristics. However, it should be noted that the tool aims to calculate a single enhanced seasonal thermal rating and thus, temperature measurements over a single day may not fully capture the temperature variation across a season.

The tool includes average seasonal temperatures for winter, summer and spring/autumn as follows;

- Winter = 10°C
- Summer = 30°C

- Spring/Autumn =20°C

These temperature values were obtained from the SPEN transformer loading guide which states the values are the maximum likely to be experienced for the respective season.

Please note that flat daily temperature profiles are used in the tool and it has been assumed that the transformer is located outdoors in free airflow. Transformers located in sheltered areas or indoors may not be suitable for enhanced thermal ratings as ambient temperatures may be higher during the winter. To use enhanced ratings for such transformers either indoor ambient temperature or top oil temperature should be recorded.

3.2.4 Connecting Assets

When considering enhanced thermal ratings, which will allow additional load to connect to a network, all connecting assets must be taken into consideration. This includes items such as switchgear, HV and LV cables, bushings, tap changers, protection and metering instruments, busbars etc. Although transformers may typically be the bottle neck, in terms of power flow, this may not always be the case.

Discussions with SPEN indicated that most assets will be suitable for up to 1.5x the transformer CMR rating however it is recommended to check connecting asset ratings on a case by case basis.

3.2.5 Aging

The Enhanced Transformer Ratings Tool has been designed using non-thermally upgraded paper and therefore aging calculations for loading to nameplate rating are based on a 98°C rated insulation temperature.

3.3 Network Integration Considerations

3.3.1 Network Protection

Protection settings may also have to be modified to prevent operation and tripping of equipment at higher loads. Protection settings to check would relate to; oil temperature, winding temperature, overload current and earth fault current.

3.3.2 Tap Changers

Load flow through transformers produces voltage drop. To boost the voltage, tap changers are used. Use of enhanced seasonal ratings could result in additional voltage drop due to increased load which in turn may cause the tap changer to operate more frequently although this may not be significantly so. Additional operations will increase wear and tear on the tap changer parts and therefore the tap changer may need more frequent maintenance. It is anticipated that the use of enhanced rating, however, will not cause significantly more operations of the tap changer as the enhanced thermal rating will only be utilised during infrequent contingency conditions.

3.3.3 Fault Level and System Losses

Increasing the amount of load connected to a transformer could result in an increase in fault level, depending on the type of load connected. For this reason it is recommended that fault level studies are carried out before using an enhanced rating. Another factor to consider is that increasing the load through a transformer will increase the losses. For fault levels and losses the case of using enhanced ratings versus replacing the transformer should be considered, as both may have similar effects.

3.4 Input Parameters

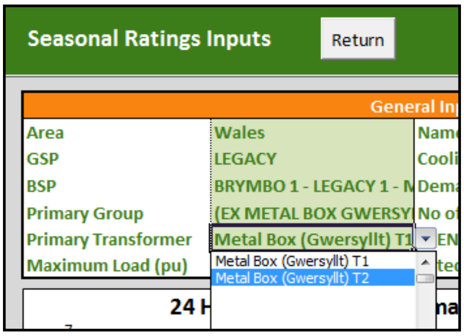
3.4.1 Primary Transformer Selection

A primary transformer is selected by using the drop down menus on the input pages. Selection should be made in the order listed below. Upon selection of one item, the lists available to the remaining menus will automatically be updated to reflect the parent item.

1. Network Area
2. GSP
3. BSP
4. Primary Group
5. Primary Transformer

These menus are automatically populated from a linked database.

Once a transformer has been selected the rating, cooling type and number of transformers in the group will be automatically populated. Figure 3-2 gives a screenshot of the drop down menus when selecting a transformer.



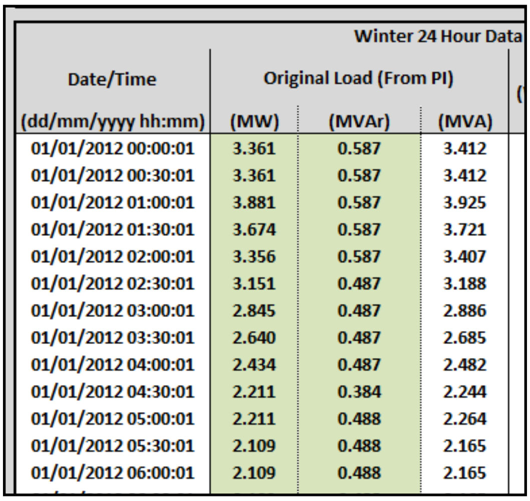
Area Wales
GSP LEGACY
BSP BRYMBO 1 - LEGACY 1 - M
Primary Group (EX METAL BOX GWERSYI
Primary Transformer Metal Box (Gwersyllt) T1
Maximum Load (pu)

Figure 3-2 Transformer selection example

For SPM, a transformer is located in a HV network group. This group is part of a BSP group and that BSP is part of a GSP group. GSPs are located in different geographic areas such as Wales or Merseyside. The SPD network connects to the transmission network at 132kV so does not include BSP groupings. To allow the program to function properly for SPD, the BSP input mirrors the GSP input.

3.4.2 Transformer Load Data

Transformer load data is required for Seasonal Ratings and Dynamic Rating functions. Upon selection of a transformer, a historic date should be input based on the highest transformer loaded day within each season. Half hourly load data is obtained from the PI server database automatically. If required the user can also enter the load data manually by overwriting the PI Tag formula in the MW and MVAr columns (see Figure 3-3). Note that the formula should either be noted so it can be replaced or the program should be saved under a different name to avoid broken links.



	Winter 24 Hour Data		
Date/Time	Original Load (From PI)		
(dd/mm/yyyy hh:mm)	(MW)	(MVAr)	(MVA)
01/01/2012 00:00:01	3.361	0.587	3.412
01/01/2012 00:30:01	3.361	0.587	3.412
01/01/2012 01:00:01	3.881	0.587	3.925
01/01/2012 01:30:01	3.674	0.587	3.721
01/01/2012 02:00:01	3.356	0.587	3.407
01/01/2012 02:30:01	3.151	0.487	3.188
01/01/2012 03:00:01	2.845	0.487	2.886
01/01/2012 03:30:01	2.640	0.487	2.685
01/01/2012 04:00:01	2.434	0.487	2.482
01/01/2012 04:30:01	2.211	0.384	2.244
01/01/2012 05:00:01	2.211	0.488	2.264
01/01/2012 05:30:01	2.109	0.488	2.165
01/01/2012 06:00:01	2.109	0.488	2.165

Figure 3-3 Transformer load data

When selecting the highest loaded day, it should first be established whether this occurred under network contingency conditions. Contingency conditions in the tool should then be set appropriately to avoid a contingency being applied twice. A contingency condition may be identifiable by studying the transformer load profile graph on the inputs page (see Figure 3-4). The sudden increase in load represents the load of a transformer being transferred onto the transformer under investigation. This increase in load is likely to be greater in SPD where transformers are designed to take up to around 50% additional load. In SPM the load is shared by up to five transformers and therefore it will be less obvious on the graph.

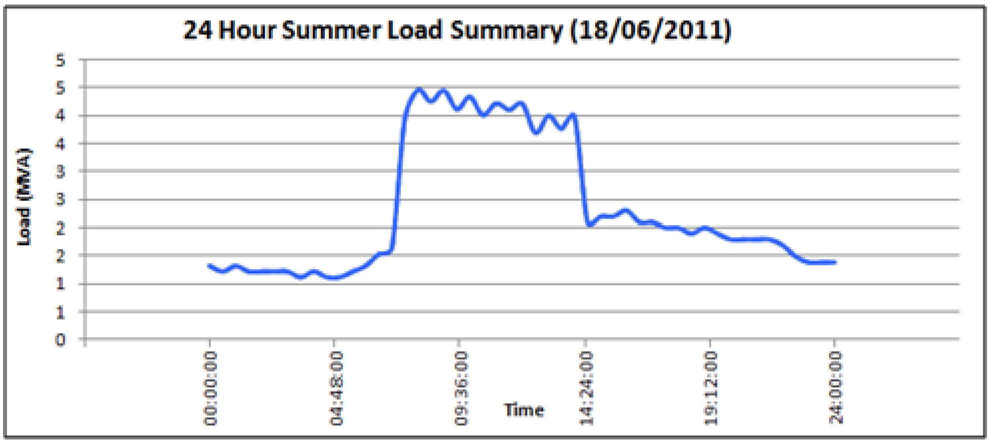
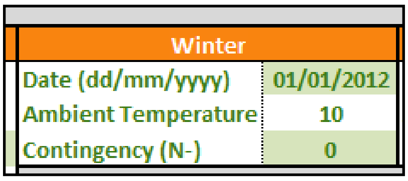


Figure 3-4 Load profile with contingency

3.4.3 Ambient Temperature

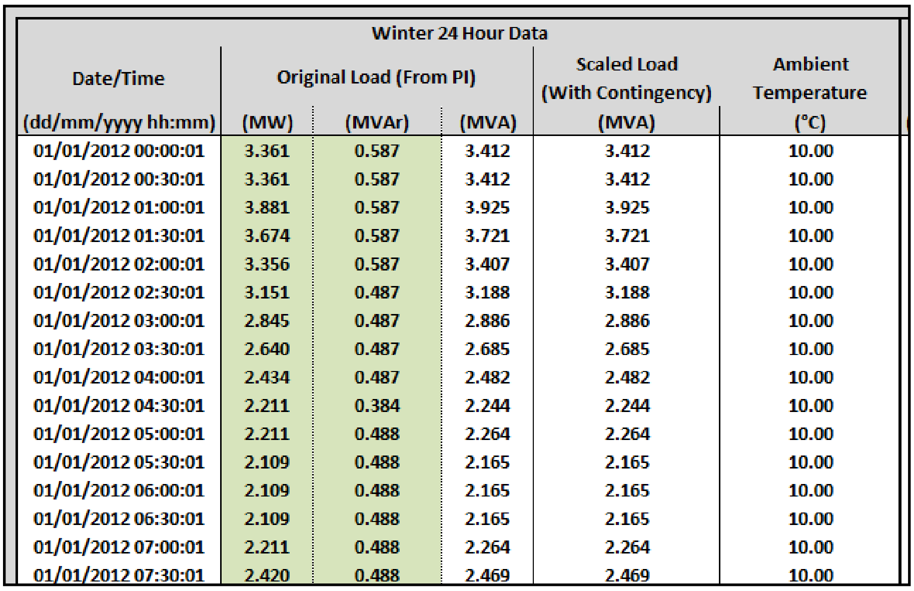
The ambient temperature is used by the thermal model to calculate the hot spot temperature as detailed in Section 2.2. The tool can accept either a single value for the ambient temperature or a temperature profile. For a single value, this should be the maximum expected ambient temperature for the duration under investigation (see Figure 3-5). All three functions require the ambient temperature input however the seasonal ratings function automatically selects this from a lookup table as detailed in section 3.2.3. The program limits the user to entering values between -50°C and +50°C.



Winter	
Date (dd/mm/yyyy)	01/01/2012
Ambient Temperature	10
Contingency (N-)	0

Figure 3-5 Ambient temperature input

For improved accuracy, a temperature profile can be used for either the Seasonal Ratings or Dynamic Rating functions. The temperature profile should be in half hourly average measurements as per the load data. Figure 3-6 shows how the ambient temperature is entered in the main inputs table.



Winter 24 Hour Data					
Date/Time	Original Load (From PI)			Scaled Load (With Contingency)	Ambient Temperature
(dd/mm/yyyy hh:mm)	(MW)	(MVAr)	(MVA)	(MVA)	(°C)
01/01/2012 00:00:01	3.361	0.587	3.412	3.412	10.00
01/01/2012 00:30:01	3.361	0.587	3.412	3.412	10.00
01/01/2012 01:00:01	3.881	0.587	3.925	3.925	10.00
01/01/2012 01:30:01	3.674	0.587	3.721	3.721	10.00
01/01/2012 02:00:01	3.356	0.587	3.407	3.407	10.00
01/01/2012 02:30:01	3.151	0.487	3.188	3.188	10.00
01/01/2012 03:00:01	2.845	0.487	2.886	2.886	10.00
01/01/2012 03:30:01	2.640	0.487	2.685	2.685	10.00
01/01/2012 04:00:01	2.434	0.487	2.482	2.482	10.00
01/01/2012 04:30:01	2.211	0.384	2.244	2.244	10.00
01/01/2012 05:00:01	2.211	0.488	2.264	2.264	10.00
01/01/2012 05:30:01	2.109	0.488	2.165	2.165	10.00
01/01/2012 06:00:01	2.109	0.488	2.165	2.165	10.00
01/01/2012 06:30:01	2.109	0.488	2.165	2.165	10.00
01/01/2012 07:00:01	2.211	0.488	2.264	2.264	10.00
01/01/2012 07:30:01	2.420	0.488	2.469	2.469	10.00

Figure 3-6: Ambient temperature profile input

Care should be taken when using actual temperature profile data as temperature may be somewhat higher or lower in the future during high loading conditions.

3.4.4 Maximum Load

The Maximum Load input is to prevent an enhanced transformer thermal rating going above a set value. This is useful for incorporating the rating of connecting assets such as bushings, tap changers, cables, switchgear etc into the tool. For example, if the bushings of the particular transformer have a maximum rating of 1.3 per unit then 1.3 can be entered. If an enhanced rating is calculated to be above 1.3 per unit, the tool will cap these at 1.3. IEC 60076-7 has a recommended maximum of 1.5 per unit. The program limits the user to entering values between 1 and 1.5. The per unit value is based on the nameplate rating entered into the program.

3.4.5 Demand Growth Scaling Factor

The demand growth scaling factor is used to scale historic load data to represent the load profile in future years or periods. Load growth is entered as a multiplier. The program limits the user to entering values between 0.1 and 10.

3.4.6 PI Server Name

The PI server name is the name of the server where the PI load database is located. This defines the formulas used to obtain historic load data.

3.4.7 Contingency

The contingency input is used to represent the level of contingency for the period under investigation. This input is used by the Seasonal Ratings and Dynamic Rating functions. The user can enter either 0, 1 or 2 via a drop down menu. 0

represents normal running conditions i.e. no contingency. 1 represents a single transformer outage. 2 represents two transformers out, either one for maintenance and the other due to fault or both due to fault. Based on these values and the number of transformers in the group the program will calculate a contingency scaling factor as detailed in Section 3.2.2.

3.4.8 Date

The date input is used by both the Seasonal Ratings and Dynamic Rating functions. For Seasonal Ratings, three dates are required; one for each season. These dates represent the day within that season which the user wishes to obtain historic load data for. This would typically be the highest loaded day within that season. For Dynamic Ratings two dates are required. These represent the start and finish date for the period under investigation.

Note that the dates should be entered in the format dd/mm/yyyy.

3.4.9 Insulation Temperature

IEC 60076-7 states that the rated insulation temperature is 98°C and the maximum insulation temperature is 140°C long term and 160°C short term. The Seasonal Ratings and Dynamic Rating functions would typically use insulation temperatures between 98°C and 140°C. The cyclic rating function would typically use an insulation temperature between 98°C and 160°C. The ability to accept a higher insulation temperature for an increase in transformer aging is key to enabling the calculation of enhanced thermal ratings above nameplate.

3.4.10 Cyclic Pre Load

The pre load input is associated with the Cyclic Rating function. This input provides the tool with a value of load that a transformer is supplying before a cyclic overload is taken. The tool will apply this value as a flat load profile for a period of 24 hour minus the cyclic duration. The program limits the user to entering values between 0.01 and 1.5.

3.4.11 Cyclic Duration

The cyclic duration input is associated with the Cyclic Rating function. This input provides the program with the length of time in minutes that the cyclic overload will be required. The program limits the user to entering values between 1 and 720 minutes.

3.4.12 Summary of Inputs

The table below provides a quick reference to the inputs used within the program. For more information on the different inputs see the relevant sections.

Input	**Entry Method**	**Used By**	**Description**	**Comments**
Area	Drop down menu	All functions	This is the area where the GSP is located i.e. Wales	Values limited to data available in group database
GSP	Drop down menu	All functions	This is the GSP which the BSP belongs to	Values limited to data available in group database
BSP	Drop down menu	All functions	This is the BSP which the primary group belongs to	Values limited to data available in group database
Primary Group	Drop down menu	All functions	This is the primary group that the transformer belongs to	Values limited to data available in group database
Primary Transformer	Drop down menu	All functions	This is the transformer that is to be studied	Values limited to data available in group database
Nameplate Rating	Automated	All functions	This is the maximum continuous rating shown on the nameplate of the transformer. If dual rating choose the higher.	Value is looked up from Group Database
Cooling Type	Automated	All functions	This is the cooling type shown on the nameplate of the transformer. If dual rating choose the cooling at the higher rating.	Value is looked up from Group Database. Value in Group Data base is looked up from Global settings.
Maximum Load	Manual input	All functions	This input can be used to represent the lowest rated component within the system. Examples include bushing, switchgear cables etc.	Value is limited to 1.5 maximum.

Input	Entry Method	Used By	Description	Comments
Demand Growth Scaling Factor	Manual input	Seasonal Ratings and Dynamic Rating	Used to scale the load data to represent the year under study. For example you may want to scale load data taken from 2012 to represent 2013. A value of 1 can be entered for no scaling.	SPEN annual scaling factors can be used for this input
No. Of Tx In Group	Automated	Seasonal Ratings and Dynamic Rating	The number of transformers in a group is used to calculate contingency scaling factors	This is calculated by the program
PI Server Name	Manual input	Seasonal Ratings and Dynamic Rating	This input is used within the PI Tags to read data from PI.	
Rated Insulation Temperature	Manual input	Seasonal Ratings and Dynamic Rating	The IEC rated insulation temperature is 98°C. At this temperature the insulation will age at a rate of 1:1 i.e. 24 hours aging for 24 hours use. User can manually change this value if they want to modify the amount of aging on the transformer.	If this value goes above 130°C the cell will highlight red to indicate to the user they are approaching potentially dangerous conditions
Maximum Insulation Temperature	Manual input	Cyclic rating	IEC maximum insulation temperature is 125°C. At this temperature the insulation will age at a rapid rate however the cyclic duration is generally not for a prolonged period of time. User can manually change this value to modify amount of aging on the transformer.	If this value goes above 130°C the cell will highlight red to indicate to the user they are approaching potentially dangerous conditions

Input	Entry Method	Used By	Description	Comments
Season Date	Manual input	Seasonal Ratings	This is the date within the season that the user wants to load historic data for.	Must be entered in the format dd/mm/yyyy. The date to be studied will most likely be the peak day within the month.
Start Date	Manual input	Dynamic Rating	User to enter the start date for the time period they want to study.	Must be entered in the format dd/mm/yyyy
Finish Date	Manual input	Dynamic Rating	User to enter the finish date for the time period they want to study.	Must be entered in the format dd/mm/yyyy
Ambient Temperature	Manual input & automated	Seasonal Ratings, Dynamic Rating and Cyclic Rating	The ambient temperature should be entered for the area surrounding the transformer.	Ambient temperature is only automated for seasonal rating as the time period is known for each season. For Dynamic and cyclic rating, which could be calculated for any time in the year, the user must enter the desired ambient temperature.
Contingency Level	Drop down menu	Seasonal Ratings and Dynamic Rating	This input is used to create a contingency scaling factor. This factor is then used to scale the historic load data to represent the additional load the transformer will see during a contingency.	Values limited to 0, 1 & 2 via the drop down menu.

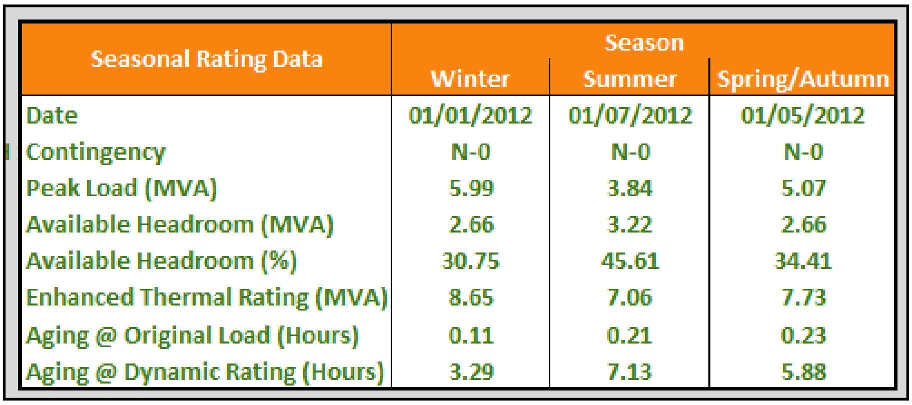
Input	**Entry Method**	**Used By**	**Description**	**Comments**
Cyclic Pre Load	Manual input	Cyclic Rating	This input provides the cyclic rating function with a flat load profile to be used before an overload has been taken	User to enter up to 10 pre load values in per unit.
Cyclic Duration	Manual input	Cyclic Rating	This input provides the cyclic rating function with overload durations	User to enter up to 5 durations in minutes.

3.5 Output Parameters

3.5.1 Seasonal Ratings & Dynamic Rating

For each season the following parameters are provided as an output and are shown in Figure 3-7:

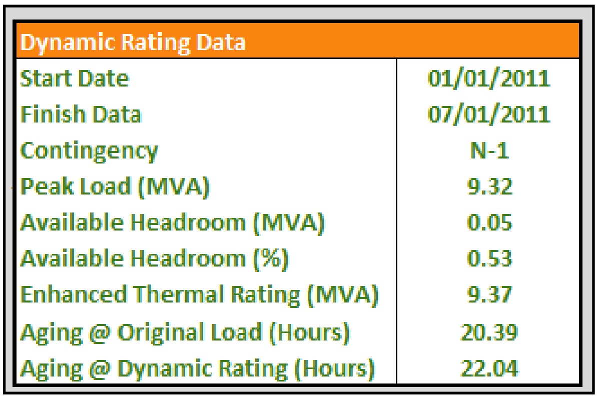
- Peak load. This value is extracted from the load profile and used to calculate the available headroom.
- Available headroom. This is calculated as the difference between the peak load and the enhanced thermal rating.
- Enhanced thermal rating.
- Aging based on normal load profile (including contingency condition). This is presented in minutes per 24 hour period.
- Aging based on enhanced thermal rating. This is presented in minutes per 24 hour period.
- In addition to the above parameters some of the input information is also presented for quick reference.



Seasonal Rating Data	Season		
	Winter	Summer	Spring/Autumn
Date	01/01/2012	01/07/2012	01/05/2012
Contingency	N-0	N-0	N-0
Peak Load (MVA)	5.99	3.84	5.07
Available Headroom (MVA)	2.66	3.22	2.66
Available Headroom (%)	30.75	45.61	34.41
Enhanced Thermal Rating (MVA)	8.65	7.06	7.73
Aging @ Original Load (Hours)	0.11	0.21	0.23
Aging @ Dynamic Rating (Hours)	3.29	7.13	5.88

Figure 3-7 Seasonal ratings summary table

For the Dynamic Rating function a similar table is produced as shown in Figure 3-8 for the loading over the defined start and finish date.



Dynamic Rating Data	
Start Date	01/01/2011
Finish Data	07/01/2011
Contingency	N-1
Peak Load (MVA)	9.32
Available Headroom (MVA)	0.05
Available Headroom (%)	0.53
Enhanced Thermal Rating (MVA)	9.37
Aging @ Original Load (Hours)	20.39
Aging @ Dynamic Rating (Hours)	22.04

Figure 3-8 Dynamic Rating summary table

The scaled load profile, transformer hot spot temperature, ambient temperature and the calculated enhanced thermal rating are plotted as shown in Figure 3-9. This provides some visualisation of the tool functionality. Key metrics are also tabulated as shown above.

It can be seen that the transformer hot spot temperature lags slightly behind the load profile due to the thermal inertia of the transformer. The area of interest which defines the enhanced rating is the peak hot spot temperature. The load is scaled up until this peak hot spot temperature reaches the rated insulation temperature specified.

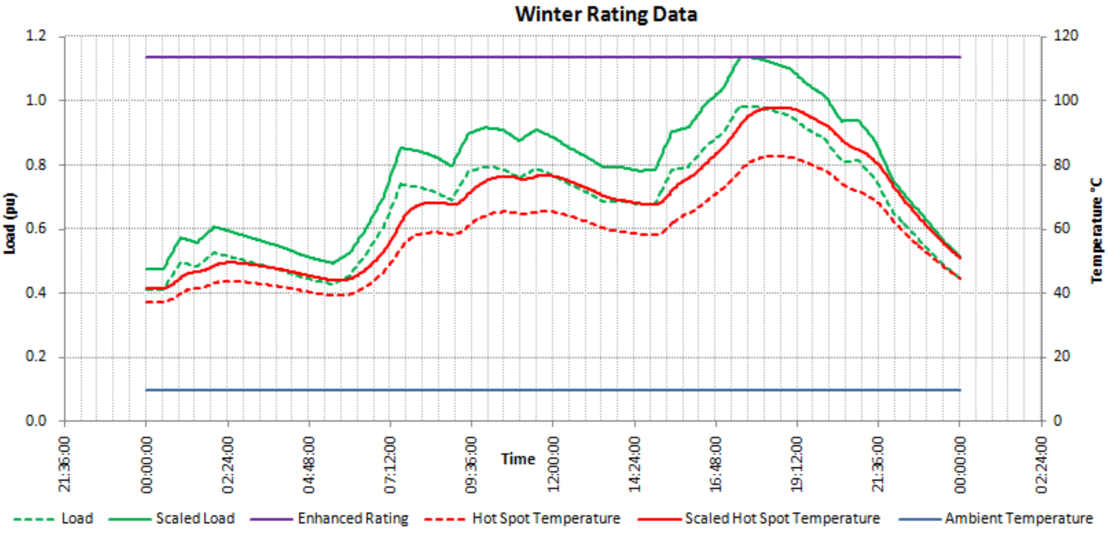


Figure 3-9 Seasonal Ratings Output Graph

Figure 3-10 shows the unscaled (original) age rate and the scaled (enhanced thermal rating) age rate. It can be seen that the age rate reaches 1 due to the model scaling the load profile up until the hot spot temperature reaches the rated insulation temperature. In this case, the rated insulation temperature is 98°C which gives an age rate of 1 i.e. 24 hours aging over a 24 hour period. If a higher value of rated insulation temperature was used, the age rate would reach a value greater than 1. Although the shape of the enhanced rating aging profile looks steep, the duration over which this loading occurs should be considered. The majority of the time, the transformer will be well below this loading hence very little aging will actually occur over the year.

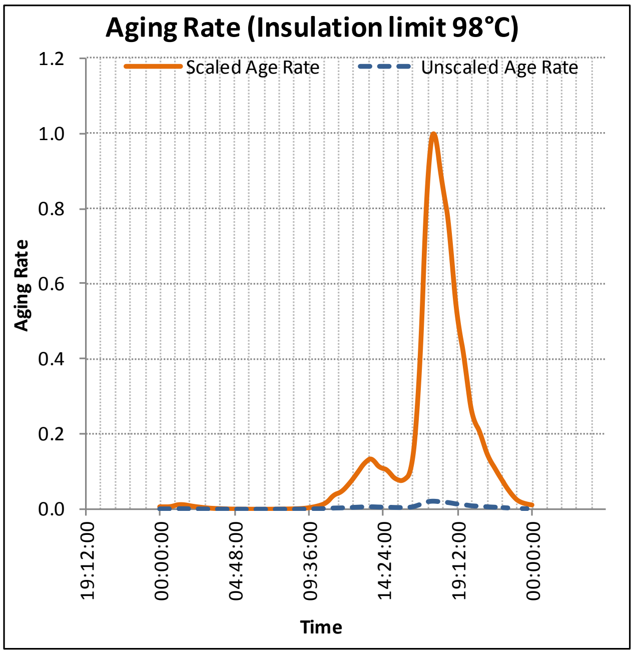


Figure 3-10 Aging Rate

3.5.2 Cyclic Rating

The cyclic rating function provides cyclic rating values in per unit against the inputted pre-load values. Each cyclic duration is plotted as a separate curve as shown in Figure 3-11. The user can then extract the appropriate pre-load value, cyclic rating and duration over which the cyclic rating can be sustained before reduction back to the pre-load value.

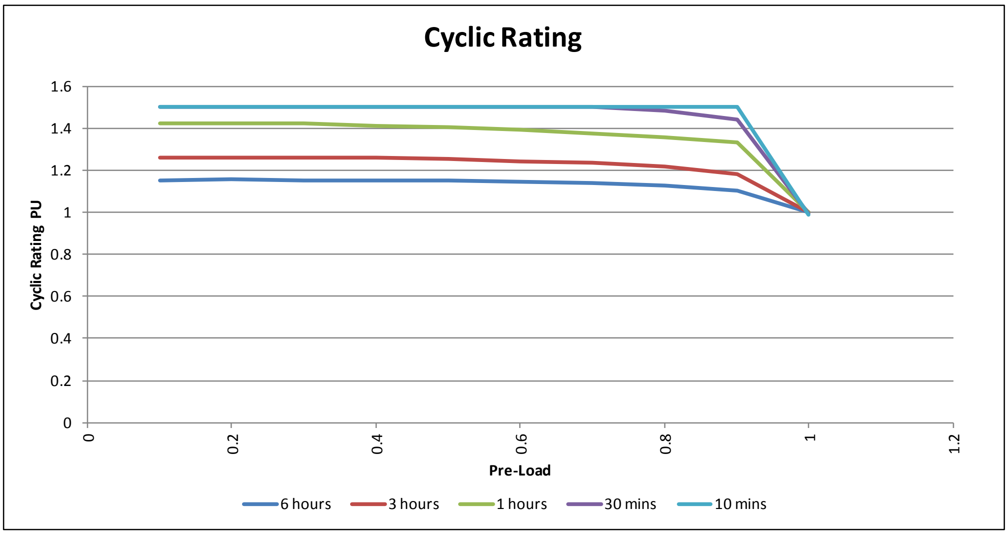


Figure 3-11 Cyclic Rating Output Graph

It can be seen that the longer the duration of overload, the lower the allowable overload is. Also, in this case an ambient temperature of 20°C was used which gives no additional overload capacity for a pre-load value of 1 per unit (nameplate rating). For a lower ambient temperature, the acceptable level of overload with a pre-load value of 1 per unit would increase.

Example: How does overload duration affect rating?

Pre-load = 0.6pu, duration = 6 hours and 3 hours.

With a pre-load of 0.6pu, a rating of 1.18pu could be achieved for 6 hours. With a pre-load of 0.6pu, a rating of 1.22pu could be achieved for 3 hours. Increasing the duration reduces the cyclic rating.

4 Case Studies

Enhanced seasonal ratings were calculated for the Flexible Networks three network trial sites using the transformer CMR rating and peak load data from 2011 along with an insulation temperature of 110°C. An N-1 contingency was applied to each seasonal load profile. It can be seen from the results that the amount of aging when using enhanced ratings is considerably higher than that aging under normal load profile. Although this aging is higher, it shouldn't be a concern as the transformer will only run at the enhanced rating for a limited period i.e. during mutual contingency and peak loading conditions.

4.1 St Andrews

St Andrews is a large town in the rural location of Fife, Scotland, with a population of approximately 17,000. St Andrews is a tourist area and is also home to the well-known St Andrews University. The primary network group of St Andrews consists of 2, 33/11kV primary transformers of 15/21MVA rating that supply the 11kV distribution network. The two transformers are located at St Andrews Primary Substation and operate in parallel with a split busbar arrangement. Under contingency conditions, the busbar will be closed so the remaining transformer can supply the full load. The 11kV circuits from this primary substation are operated radially but with the facility to be interconnected to neighbouring networks following a system outage.

St Andrews T1 Transformer Rating: 15 MVA ONAN / 21 MVA ONAF (CMR), with no CER rating.

Table 4-1 gives key results. The enhanced ratings are based on an insulation temperature of 110°C.

Table 4-1 St Andrews T1 Results

Data	Winter	Summer	Spring/Autumn
Peak Load (MVA)	15.01	11.30	14.37
Enhanced Thermal Rating (MVA)	25.45	22.17	23.65
Increase from CMR (MVA)	4.45	1.17	2.65
Aging @ Original Load (Hours)	0.12	0.26	0.31
Aging @ Enhanced Rating (Hours)	18.91	23.75	26.22

St Andrews T2 Transformer Rating: 15 MVA ONAN / 21 MVA ONAF (CMR), with no CER rating.

Table 4-2 St Andrews T2 Results

Data	Winter	Summer	Spring/Autumn
Peak Load (MVA)	19.78	14.97	15.29
Enhanced Thermal Rating (MVA)	26.07	21.91	23.60
Increase from CMR (MVA)	5.07	0.91	2.60
Aging @ Original Load (Hours)	1.07	1.00	0.36
Aging @ Enhanced Rating (Hours)	31.06	23.74	22.28

It can be seen that there are slight differences in enhanced ratings between the two transformers at St Andrews. This is due to variations in load profiles as the two transformers supply different feeders (split busbar arrangement) and the analysis tool scales the load by a factor of 2 for a group of two transformers. The analysis tool could be refined in future by summating the actual measured load for both transformers when simulating contingency conditions, based on the peak aggregated load.

4.2 Ruabon

Ruabon is a small village located in the borough of Wrexham, Wales, with a population of approximately 2500. The Ruabon 33/11kV system consists of one 7.5/10MVA 33/11kV primary transformer which supplies the 11kV distribution network. The 11kV circuits from this primary substation are operated radially but with the facility to be interconnected to neighbouring networks supplied from Llangollen, Johnstown, Monsanto and Maelor Creamery following a system outage.

Ruabon T1 Transformer Rating: 7.5 MVA ONAN / 10 MVA ONAF (CMR), with no CER rating.

Table 4-3: Ruabon T1 Results

Data	Winter	Summer	Spring/Autumn
Peak Load (MVA)	11.08	6.80	9.45
Enhanced Thermal Rating (MVA)	12.34	10.55	11.48
Increase from CMR (MVA)	2.34	0.55	1.48
Aging @ Original Load (Hours)	2.73	0.63	1.31
Aging @ Enhanced Rating (Hours)	11.65	17.42	10.34

4.3 Whitchurch

Whitchurch is a market town in Shropshire with a population of approximately 9000. The 33/11kV system, in Whitchurch, consists of three 33/11kV primary transformers that supply the 11kV distribution network, Whitchurch, Liverpool Road and Yockings Gate. Under no contingencies these are connected radially with the capability of being interconnected when a contingency does occur.

Whitchurch Transformer Rating: 7.5 MVA ONAN / 10 MVA ONAF (CMR), with no CER rating.

Table 4-4: Whitchurch Results

Data	Winter	Summer	Spring/Autumn
Peak Load (MVA)	8.64	6.35	8.04
Enhanced Thermal Rating (MVA)	12.53	10.65	11.53
Increase from CMR (MVA)	2.53	0.65	1.53
Aging @ Original Load (Hours)	0.20	0.53	0.41
Aging @ Enhanced Rating (Hours)	9.07	25.95	11.14

Liverpool Road Transformer Rating: 7.5 MVA ONAN (CMR), with no CER rating and 10MVA for 3 hours cyclic rating)

Table 4-5: Liverpool Road Results

Data	Winter	Summer	Spring/Autumn
Peak Load (MVA)	7.63	4.47	7.28
Enhanced Thermal Rating (MVA)	9.46	8.23	8.58
Increase from CMR (MVA)	1.96	0.73	1.08
Aging @ Original Load (Hours)	1.65	0.23	2.79
Aging @ Enhanced Rating (Hours)	24.07	18.54	16.66

Yockings Gate Transformer Rating: 7.5 MVA ONAN / 10 MVA ONAF (CMR), with no CER rating.

Table 4-6 Yockings Gate Results

Data	Winter	Summer	Spring/Autumn
Peak Load (MVA)	7.46	8.02	5.84
Enhanced Thermal Rating (MVA)	12.81	11.47	11.73
Increase from CMR (MVA)	2.81	1.47	1.73
Aging @ Original Load (Hours)	0.12	0.65	0.08
Aging @ Enhanced Rating (Hours)	21.22	8.57	12.38

4.4 Firm Capacity Comparison

From the enhanced ratings analysis above, new firm capacities can be calculated for the HV network groups based on an N-1 contingency. Table 4-7 shows a comparison between the existing firm capacity and the new enhanced seasonal firm capacities. It can be seen that for all three transformer HV groups, the new winter firm capacity (during which load is expected to be greatest) is higher than the existing firm capacity. The Whitchurch HV group has the least gain as it includes a 7.5 MVA transformer (Liverpool Road) which only has a 10 MVA cyclic overload as opposed to a 10 MVA CMR rating. The enhanced ratings used to calculate these firm capacities have been based on an insulation temperature of 110°C. This has minimal additional aging implications and still provides a large margin from the maximum acceptable insulation temperature of 160°C.

Table 4-7 Firm Capacity Comparison

HV Group	Firm Capacity (MVA)				
	Existing	Winter	Summer	Spring/Autumn	Winter Capacity Increase
St Andrews	21	25.45	21.91	23.60	21%
Ruabon	10	12.34	10.55	11.48	23%
Whitchurch	20	21.99	18.88	20.11	10%

It can be seen from the table above that Whitchurch has a lower than existing firm capacity during summer. This is due to the fact that the current firm capacity is based on the Liverpool Road transformer having a 10 MVA cyclic rating for 3 hours. The enhanced ratings are calculated using the CMR rating which is 7.5 MVA.

5 Sensitivity Studies

5.1 Model Validation

It is understood that transformer designers typically use an insulation temperature of circa 120°C for defining CER ratings. The CER rating was recreated for a primary transformer with an ONAN rating of 12MVA, a CMR of 19MVA and a CER of 24MVA based on this insulation temperature.

A primary transformer was defined in the tool as 19MVA ONAF CMR. Setting the ambient temperature to 5°C, the insulation temperature was increased from 98°C until the enhanced rating was close to 24MVA. This occurred at an insulation temperature of 115°C (24.39MVA). This provides some additional verification of the analysis tool and the underlying algorithm.

5.2 Rating Dependencies

5.2.1 Ambient Temperature

Primary Transformer: 7.5MVA ONAN (Liverpool Road)

Insulation temperature: 98°C

Load profile: Flat @ 7.5 MVA & Scaled Winter Peak N-0 (16/12/2011), see *Figure 5-1* for unscaled load profile.

As can be seen from *Figure 5-2*, the relationship between the rating of the transformer and the ambient temperature is inversely proportional. For a flat load profile, temperatures below 20°C result in a rating greater than the nameplate rating. This is consistent with the nameplate rating being based on a 20°C ambient temperature and an insulation temperature of 98°C. When an actual load profile is used, the relationship and shape of the graph remain the same. The key difference, however, is that the shape of the load profile allows for a higher rating because the transformer only spends a short time at the peak load.

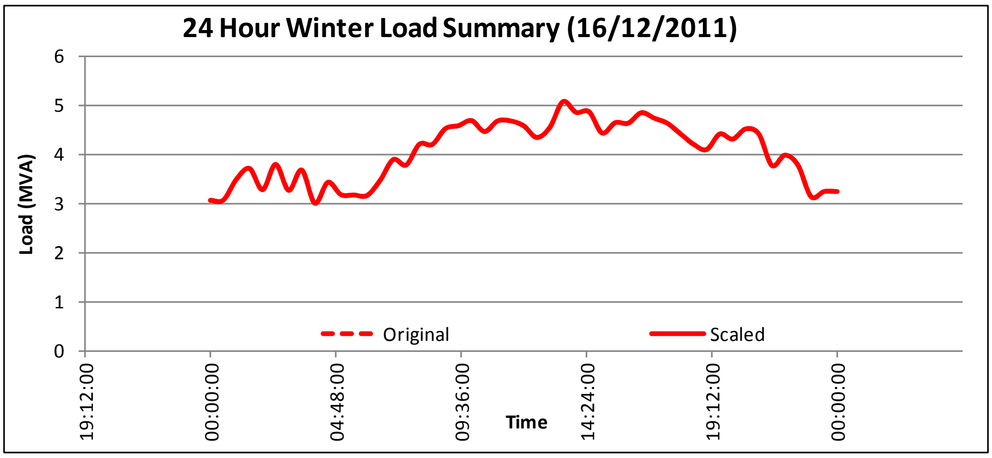


Figure 5-1 Liverpool Road Primary Transformer Winter Peak

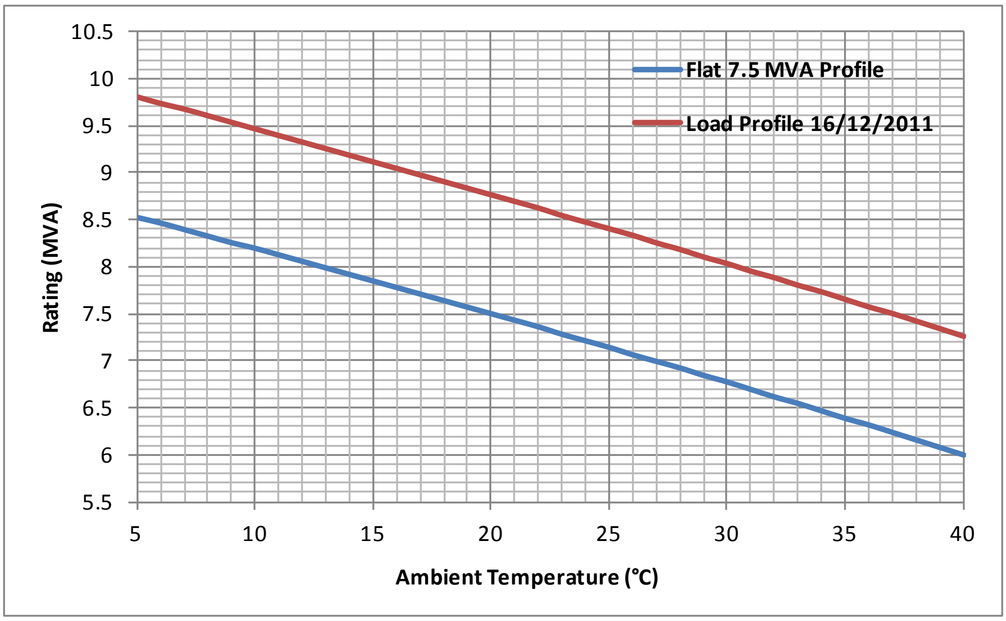


Figure 5-2 Rating Vs Ambient Temperature

5.2.2 Insulation Temperature

Primary Transformer: 7.5MVA ONAN (Liverpool Road)

Ambient temperature: 20°C

Load profile: Flat @ 7.5 MVA & Scaled Winter Peak N-0 (16/12/2011), see *Figure 5-1* for unscaled load profile.

As can be seen from *Figure 5-3*, the relationship between the rating of the transformer and the insulation temperature is almost linear. For a flat load profile, an insulation temperature of 98°C gives a rating of 7.5 MVA as expected. Use of the actual load profile gives a higher rating due to the profile shape.

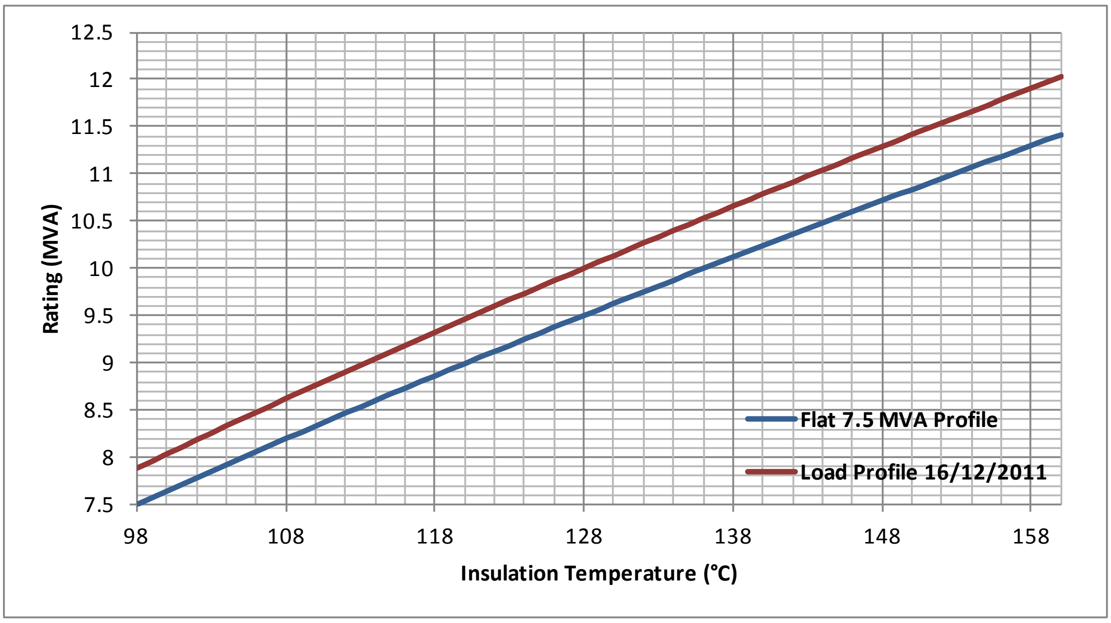


Figure 5-3 Rating Vs Insulation Temperature

5.3 Aging Dependencies

5.3.1 Ambient Temperature

Primary Transformer: 7.5MVA ONAN (Liverpool Road)

Insulation temperature: 98°C

Load profile: Flat @ 7.5 MVA & Scaled Winter Peak N-0 (16/12/2011), see *Figure 5-1* for unscaled load profile.

It can be seen from *Figure 5-4*, that the use of the flat 7.5MVA profile gives higher aging results compared to the real load profile. This is due to the real load profile being lower than 7.5 MVA for the majority of the time. This figure also shows that the relationship between the aging rate of the insulation and the ambient temperature is exponential. At an ambient temperature of 20°C, the resulting age rate is 24 hours per day when the flat load profile is used.

Figure 5-5 shows the real load profile plot. The same exponential relationship can be seen however, the aging rate is significantly lower.

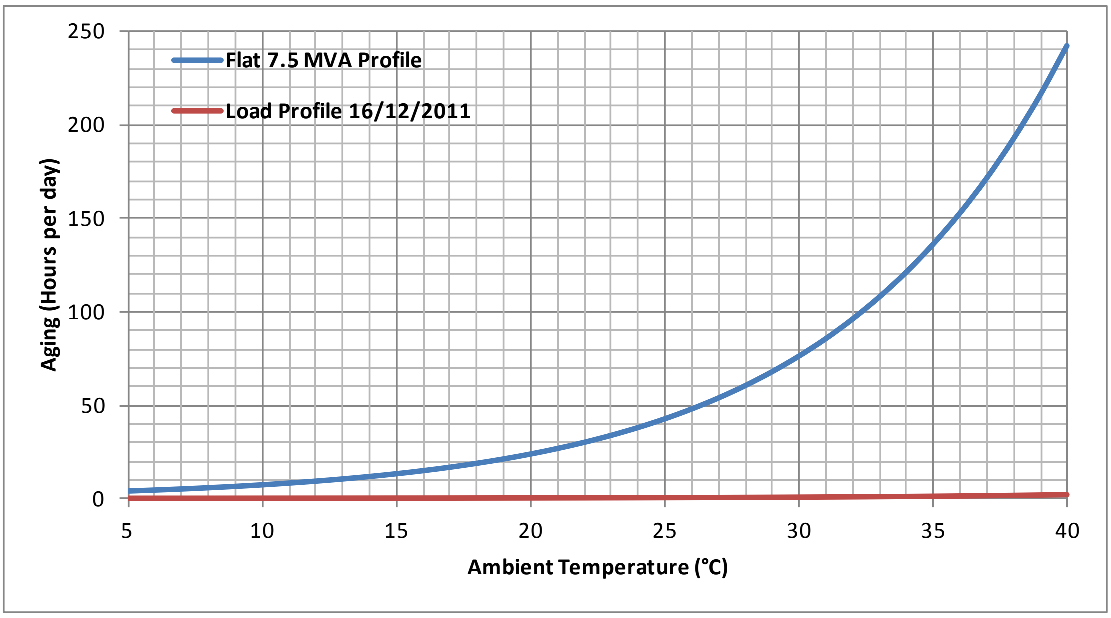


Figure 5-4 Aging Vs Ambient Temperature (flat load profile)

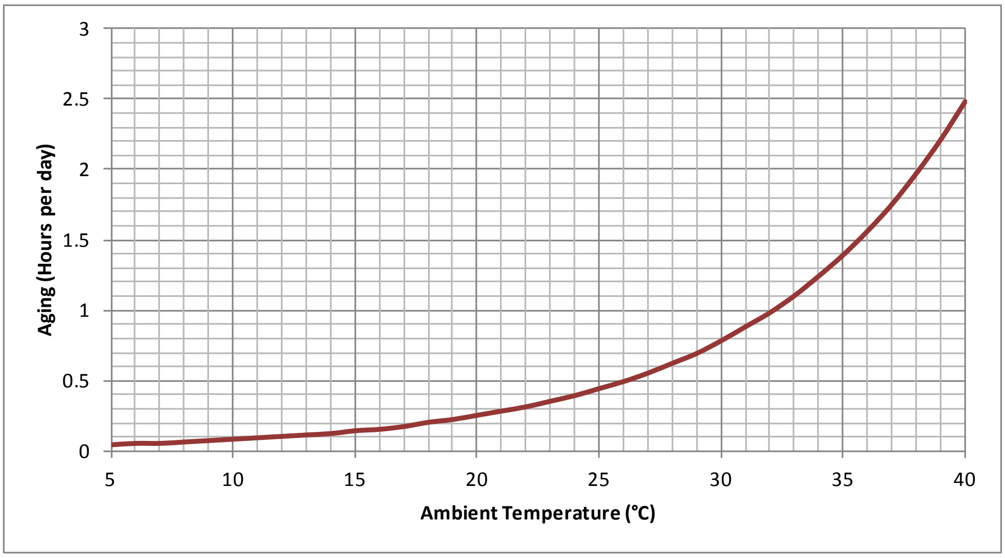


Figure 5-5 Aging Vs Ambient Temperature (real load profile)

5.3.2 Insulation Temperature

Primary Transformer: 7.5MVA ONAN (Liverpool Road)

Ambient temperature: 20°C

Load profile: Flat @ 7.5 MVA & Scaled Winter Peak N-0 (16/12/2011), see *Figure 5-1* for unscaled load profile.

As can be seen from *Figure 5-6*, the relationship between the aging rate of the insulation and the insulation temperature is exponential. An insulation temperature of 98°C results in 24 hours per day aging, for the flat load profile as expected. The actual load profile produces significantly less aging due to the lower loading levels for much of the time.

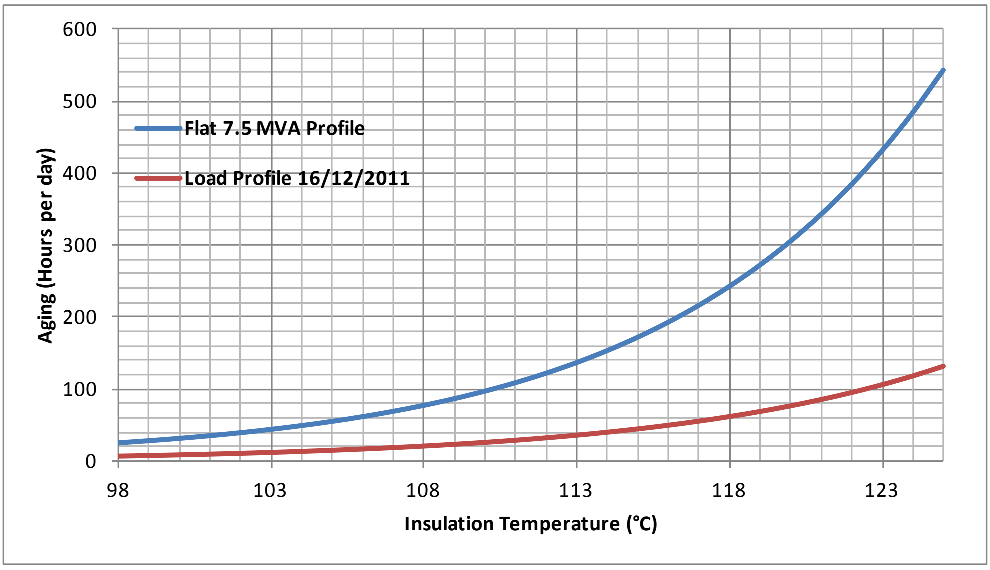


Figure 5-6 Aging Vs Insulation Temperature

5.3.3 Aging Worked Example

The DNV GL analysis provides transformer aging for a range of typical load profiles. Using aging rates calculated for contingency conditions and for normal network loading conditions, the overall impact of enhanced thermal ratings on transformer aging can be characterised. The following example provides an illustration of this.

Transformer Rating: 21 MVA ONAF (CMR), 98°C insulation temperature

Normal load profile - 361 days (10.7MVA peak) gives an aging rate of 0.07 days/year

Contingency load profile - 4 days (~21MVA peak) gives an aging rate of 0.3 days/year/day

Total Aging is 0.07 + 0.3x4 = 1.27 days/year

This shows that operation during contingency conditions is a key contributor to asset aging however, this is not significant compared to a design age rate of 1 day/day and would only occur when contingency loading was approaching the enhanced thermal rating.

Figure 5-7 provides results for aging with a range of insulation temperatures under contingency conditions and aging due to the normal load profile. This example is for a two transformer group. For a meshed HV network containing a larger number of transformers, loading and thus aging under normal conditions and contingency conditions will be more comparable.

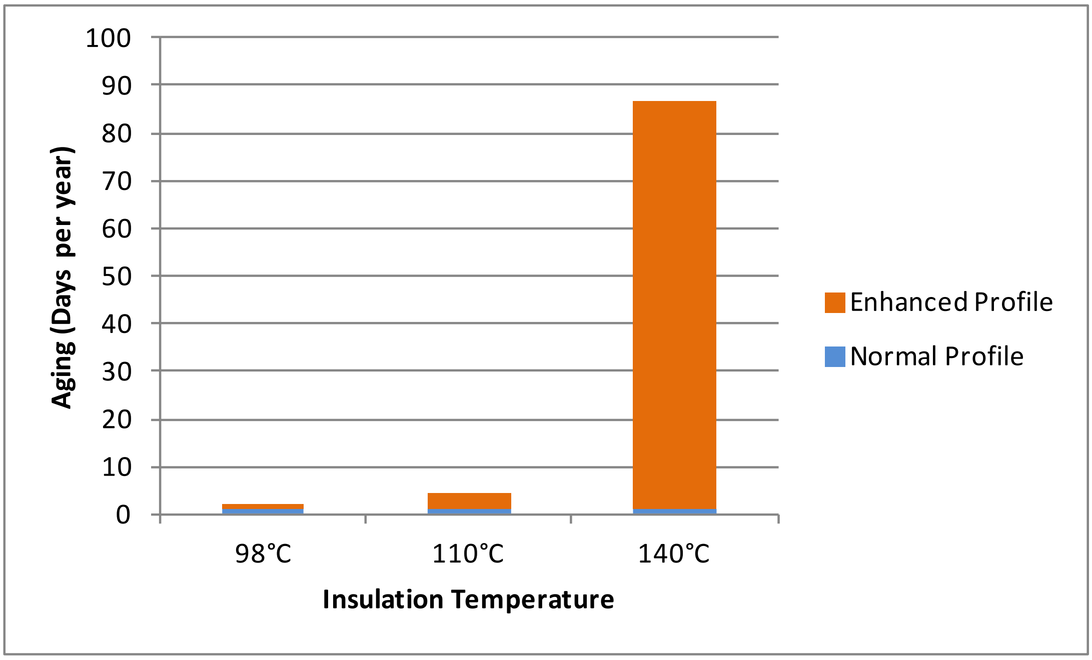


Figure 5-7 Aging with Insulation Temperature

6 Future Work

In order to develop the Enhanced Transformer Ratings Tool further for integration into SPEN business-as-usual, the following issues and enhancements should be considered.

6.1 Changes to Network Policy and Practice

6.1.1 Automation

Enhanced seasonal ratings for primary transformers should replace existing nameplate ratings in the distribution operational management system (GE PowerOn), and the network analysis tools (e.g. IPSA and DigSilent). Within the IPSA software package there is the ability to enter additional ratings for transformers.

Enhanced ratings should also be automatically recalculated and updated annually. This activity would need to be captured in the transformer application and policy and the HV network design guide as well as implemented in business processes.

6.1.2 Further measurements

Top oil temperature can be used as an input into the thermal model to further refine the model. For this to be implemented, transformers must be fitted with monitoring equipment to record top oil temperature.

Temperature measurements obtained from weather stations located at or near transformers with enhanced thermal ratings applied will improve the characterisation of local weather conditions.

Storage and analysis of measured data would need to be described in network planning practice. This would also need to be included in the tool as a selectable input and ideally automated.

6.1.3 Database Linkages

Transformer cooling type and ratings at the corresponding cooling type should be automatically available from a linked (GIS) database in order to select the appropriate thermal model parameters.

Ratings of connecting assets should be easily extractable from the SAP or GIS database. Reverse power flow capability of primary transformers should also be noted in the SAP database.

In future, heat run test data should be requested from the manufacturers for new transformers to improve model thermal parameters used if enhanced thermal ratings are later applied to transformers.

6.2 Tool Modifications and Improvements

Ideally, the transformer group database will automatically update to reflect new or decommissioned transformers or when a transformer details are modified.

Improved characterisation of transformer aging and remaining life could be included in the algorithms that consider historical and forecast load profiles and contingency conditions. This would be a material task due to the large amount of load data and processing time involved and may work best as standalone software.

In future, the tool could automatically search the PI database to locate the highest loaded seasonal days. This feature may be work best as an independent program in a 'common' library of data analysis tools as other network planning tools may benefit from this.

Detailed help menus should be integrated into the tool to assist the user.

7 References

[1] IEC 60076-7:2005 Loading guide for oil-immersed power transformers, page 31, figure 10.

[2] IEC 60076-7:2005 Loading guide for oil-immersed power transformers, page 53, table E.1.

[3] IEC 60076-7:2005 Loading guide for oil-immersed power transformers, page 16, equation 2.

[4] IEC 60076-7:2005 Loading guide for oil-immersed power transformers, page 16, table 2.

For additional information on the topics discussed in this report, the following documents were used:

(1) Prototyping Dynamic Transformer Thermal Rating Tool Based on IEC 60076-7, internal document, Ian Elders, July 2013

(2) IEC 60076-7:2005 Loading guide for oil-immersed power transformers

(3) IEC 60076-2:1993 - 2004 Temperature rise.

(4) ENA TS 35-2 Issue 5 – June 2007 Emergency Rated System Transformers 33/11.5kV Delta/Star and Star/Star Connected

(5) ENA TS 35-3 Issue 1 – January 2009 Continuous Maximum Rated (CMR) System Transformers (for use on systems up to 132kV)

(6) BSEN 60085:2008 Electrical Insulation – Thermal evaluation and designation

(7) IEC 60137:2003 – 2008 Insulated bushings for alternating voltages above 1000V

(8) Power Systems Transformer Loading Guide TRAN-01-008 Issue 1

(9) Power System Manweb Primary Transformer Application and Rating Policy TRAN-01-004 Issue 10

Appendix A - Tool Navigation

General

Navigation around the program is achieved by use of buttons embedded within each page. The main navigational and command buttons are placed in a toolbar at the top of the page. This toolbar will remain at the top even when the user scrolls down the page. It is recommended to only navigate using the buttons rather than using the tabs at the bottom of the Excel window. This is due to some buttons containing additional code which performs tasks other than just moving from one page to another. Failure to use the buttons could result in maloperation of the program.

Users are only required to enter values on the relevant input pages. These cells are coloured light green, with all other cells being lock for editing. Cells cannot unlocked for program modifications by clicking the ‘Unprotect Sheets’ button on the Main Menu page and entering the password. Upon reopening the program the sheets will be protected again.

Main Menu

The first page of the tool is the main menu which contains buttons to open other pages. The most common of these are the three main functions; Seasonal Ratings, Dynamic Rating and Cyclic Rating. The user also has the option to visit the Program Map, Group Database or Global Settings. Figure A-1 shows a snap shot of the Main Menu display.

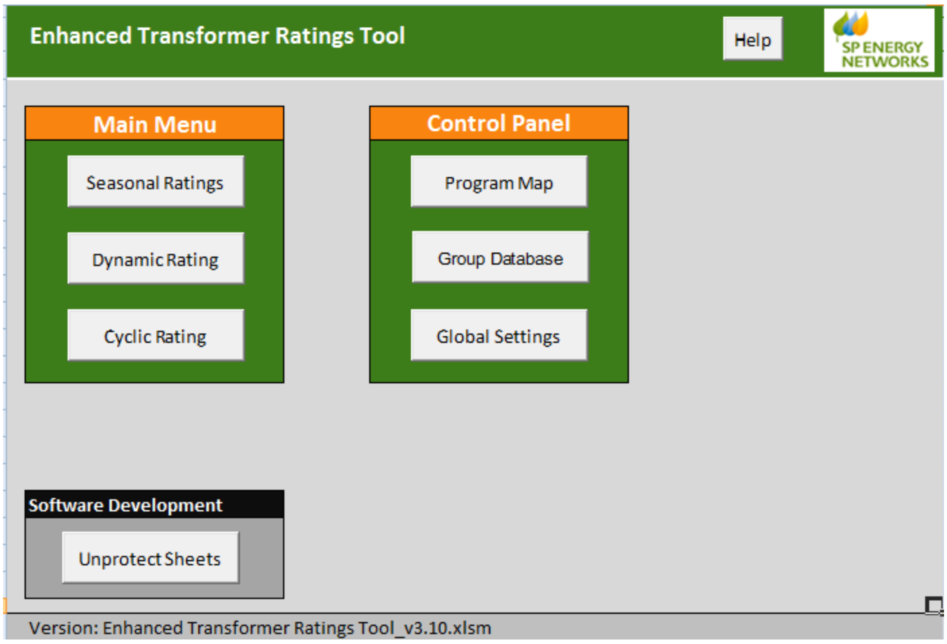


Figure A-1 Main Menu

Function Pages

There are three main calculations that the program can perform;

- Seasonal ratings
- Dynamic rating
- Cyclic rating

Each of these functions can be access via the Main Menu. The functions open up onto a main page which generally displays a summary of the input parameters and the output results. On the main page toolbar are the buttons which perform the calculations. Each function also has an input and output page, accessible via the toolbar.

Program Map

The program map can be accessed from the Main Menu via the 'Program Map' button. It provides a graphical representation of the physical structure of the program and the links between the different pages. The user may find this useful when performing program modifications. Figure A-2 shows a screenshot of the program map.

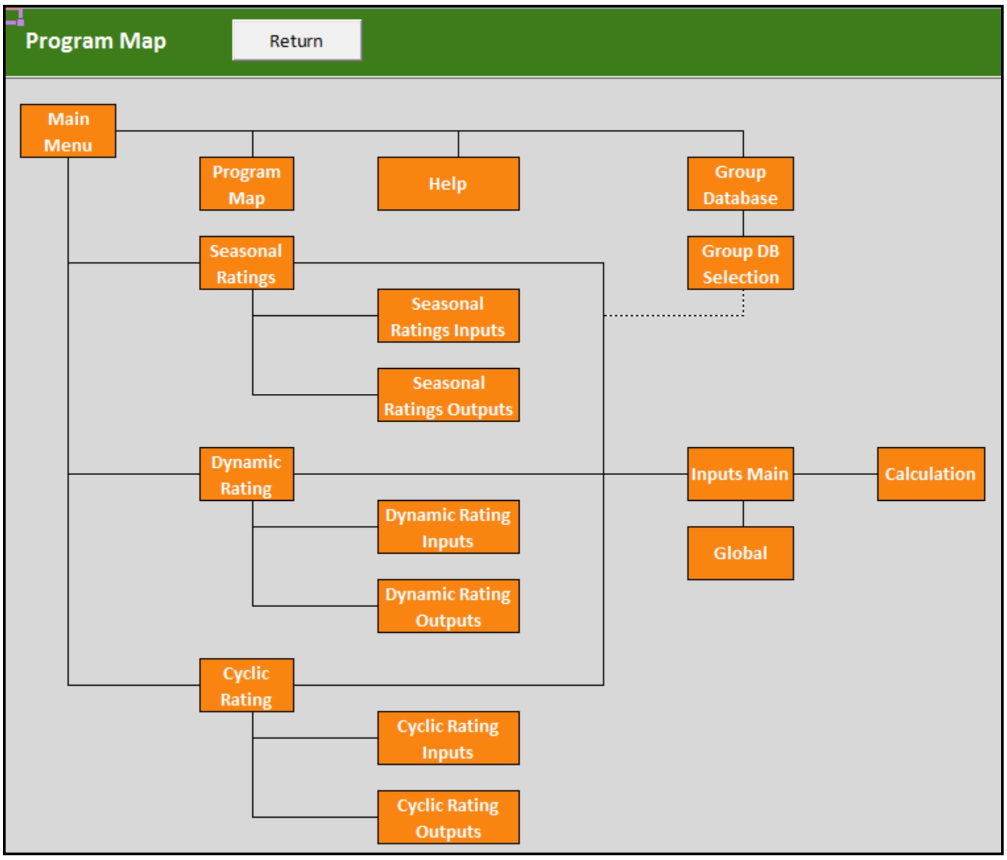
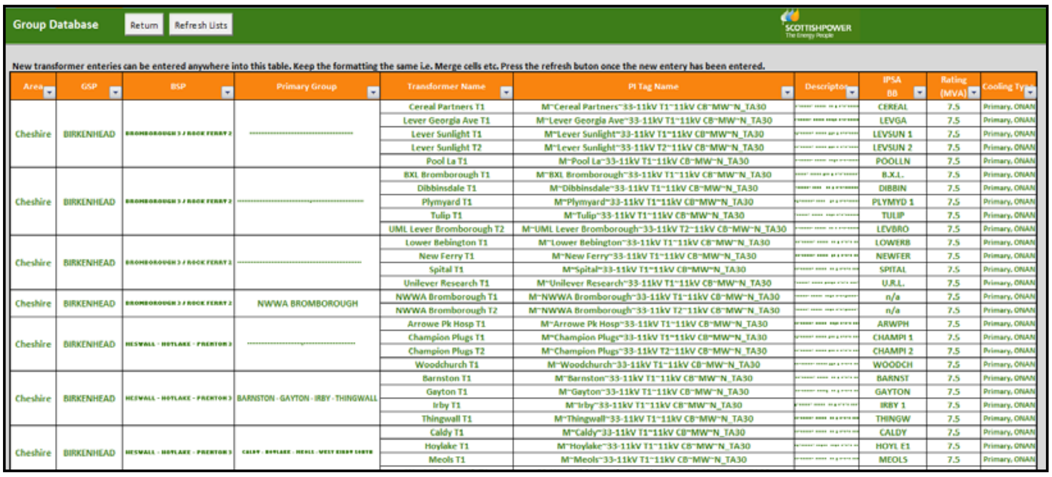


Figure A-2 Program Map

Group Database

The group database can be accessed from the Main Menu. The group database is a large table containing information such as area, GPS, BSP, Primary Group, Transformer name, Transformer PI Tag, Transformer Rating and Cooling type (note the cooling type is currently looked up from the Global sheet). To allow the program to function for both SPM and SPD, BSP entries have been made equivalent to the GSP for SPD. This means the user will have to enter the GSP in twice for SPD; once in the GSP column and again in the BSP column.

Any changes to the network configuration or transformers should be reflected in this table. Figure A-3 shows a screenshot of the group database.



New transformer enteries can be entered anywhere into this table. Keep the formatting the same i.e. Merge cells etc. Press the refresh buton once the new entery has been entered.

Area	GSP	BSP	Primary Group	Transformer Name	PI Tag Name	Descriptor	IPSA BB	Rating (MVA)	Cooling Typ
Cheshire	BIRKENHEAD	BROMBOROUGH 3 / ROCK FERRY 2	[illegible]	Cereal Partners T1	M~Cereal Partners~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	CEREAL	7.5	Primary, ONAN
				Lever Georgia Ave T1	M~Lever Georgia Ave~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	LEVGA	7.5	Primary, ONAN
				Lever Sunlight T1	M~Lever Sunlight~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	LEVSUN 1	7.5	Primary, ONAN
				Lever Sunlight T2	M~Lever Sunlight~33-11kV T2~11kV CB~MW~N_TA30	[illegible]	LEVSUN 2	7.5	Primary, ONAN
				Pool La T1	M~Pool La~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	POOLLN	7.5	Primary, ONAN
Cheshire	BIRKENHEAD	BROMBOROUGH 3 / ROCK FERRY 2	[illegible]	BXL Bromborough T1	M~BXL Bromborough~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	B.X.L.	7.5	Primary, ONAN
				Dibbinsdale T1	M~Dibbinsdale~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	DIBBIN	7.5	Primary, ONAN
				Plymyard T1	M~Plymyard~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	PLYMYD 1	7.5	Primary, ONAN
				Tulip T1	M~Tulip~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	TULIP	7.5	Primary, ONAN
				UML Lever Bromborough T2	M~UML Lever Bromborough~33-11kV T2~11kV CB~MW~N_TA30	[illegible]	LEVBRO	7.5	Primary, ONAN
Cheshire	BIRKENHEAD	BROMBOROUGH 3 / ROCK FERRY 2	[illegible]	Lower Bebington T1	M~Lower Bebington~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	LOWERB	7.5	Primary, ONAN
				New Ferry T1	M~New Ferry~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	NEWFER	7.5	Primary, ONAN
				Spital T1	M~Spital~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	SPITAL	7.5	Primary, ONAN
				Unilever Research T1	M~Unilever Research~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	U.R.L.	7.5	Primary, ONAN
Cheshire	BIRKENHEAD	BROMBOROUGH 3 / ROCK FERRY 2	NWWA BROMBOROUGH	NWWA Bromborough T1	M~NWWA Bromborough~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	n/a	7.5	Primary, ONAN
				NWWA Bromborough T2	M~NWWA Bromborough~33-11kV T2~11kV CB~MW~N_TA30	[illegible]	n/a	7.5	Primary, ONAN
Cheshire	BIRKENHEAD	HESWALL - HOYLAKE - PRENTON 3	[illegible]	Arrowe Pk Hosp T1	M~Arrowe Pk Hosp~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	ARWPH	7.5	Primary, ONAN
				Champion Plugs T1	M~Champion Plugs~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	CHAMPI 1	7.5	Primary, ONAN
				Champion Plugs T2	M~Champion Plugs~33-11kV T2~11kV CB~MW~N_TA30	[illegible]	CHAMPI 2	7.5	Primary, ONAN
				Woodchurch T1	M~Woodchurch~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	WOODCH	7.5	Primary, ONAN
Cheshire	BIRKENHEAD	HESWALL - HOYLAKE - PRENTON 3	BARNSTON - GAYTON - IRBY - THINGWALL	Barnston T1	M~Barnston~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	BARNST	7.5	Primary, ONAN
				Gayton T1	M~Gayton~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	GAYTON	7.5	Primary, ONAN
				Irby T1	M~Irby~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	IRBY 1	7.5	Primary, ONAN
				Thingwall T1	M~Thingwall~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	THINGW	7.5	Primary, ONAN
Cheshire	BIRKENHEAD	HESWALL - HOYLAKE - PRENTON 3	[illegible]	Caldy T1	M~Caldy~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	CALDY	7.5	Primary, ONAN
				Hoylake T1	M~Hoylake~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	HOYL E1	7.5	Primary, ONAN
				Meols T1	M~Meols~33-11kV T1~11kV CB~MW~N_TA30	[illegible]	MEOLS	7.5	Primary, ONAN

Figure A-3 Group Database

Global Settings

The global settings page can be access from the Main Menu. This page contains lookup tables used by the program.

Help

The help pages can be accessed from the Main Menu or from any of the main pages of the different function types.

The help menu contains the following chapters:

- General
- Seasonal Ratings
- Dynamic Rating
- Cyclic Rating
- Assumptions

The user can refer to these chapters for guidance on how to use certain parts of the program. Navigational buttons can be used to jump to the chapter of interest as can be seen from Figure A-4.

Figure A-4 Help menu

Appendix B - Correlation of Ambient Temperature and Transformer Loading

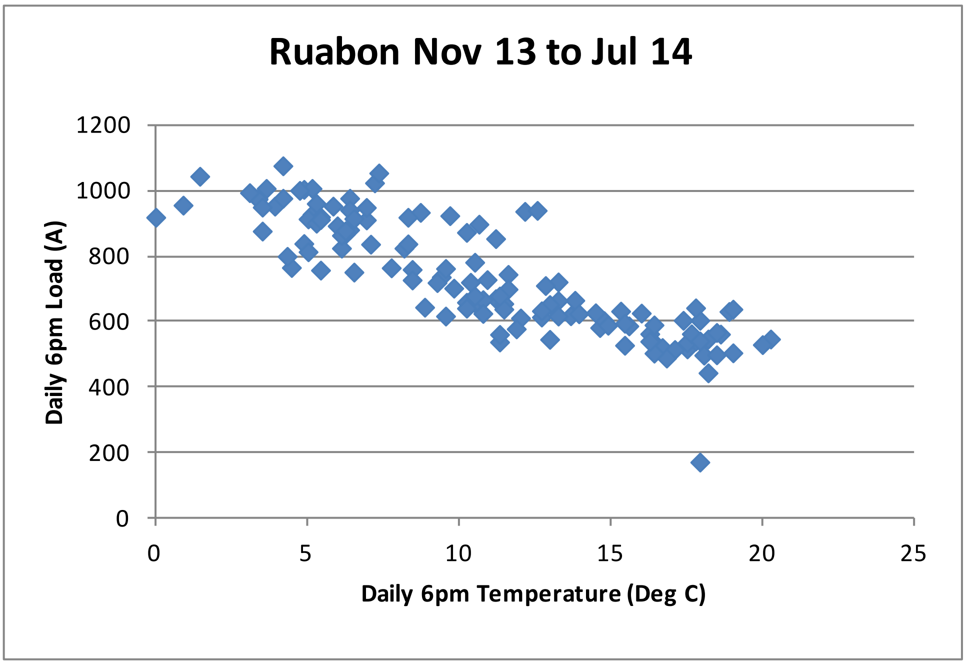


Figure B1 Correlation of ambient temperature and load for Ruabon primary transformer

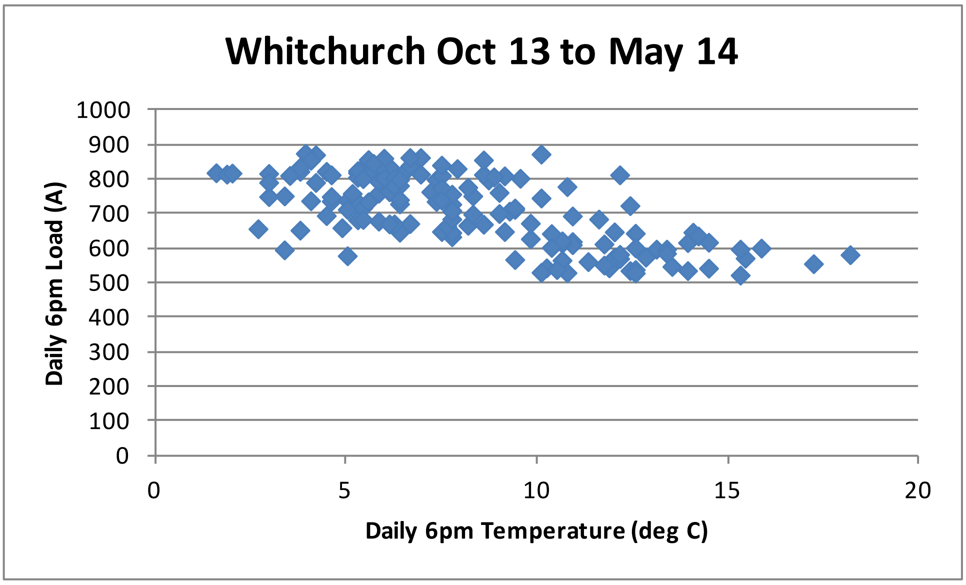


Figure B2 Correlation of ambient temperature and load for Whitchurch primary transformer

Appendix C - Stakeholder Engagement

Table C1 Table of SPEN Stakeholders Consulted During Tool Development

Name	Job Title	Department
Alan Collinson	Engineering Specialist	SPM Future Networks
Miles Buckley	Senior Design Engineer	SPM System Design
Geoff Wood	Lead Engineer (Asset Risk)	SPM Asset Management
Watson Peat	Lead Engineer	SPD Future Networks
Graeme Vincent	Lead Engineer (Load Related)	SPD Asset Management
Cornel Brozio	Analysis Manager	SPD System Design
Elena Chalmers	Lead Engineer	SPD System Design
David Carson	Manager	SPD System Design
Gordon Kelly	Lead Engineer	SPD System Design
Grant McBeath	Control Engineer	SPD Network Operations
Graham Denton	Control Engineer	SPD Network Operations
Steve Holmes	Data Integrity Administrator (GIS)	SPM Application Support
John Knott	Control Room Manager	SPM Network Operations