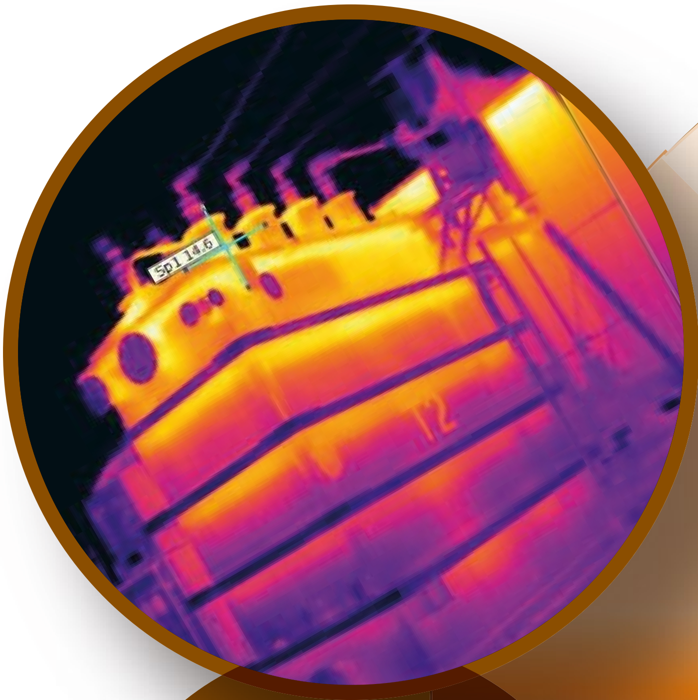
SP ENERGY NETWORKS

Flexible Networks for a Low Carbon Future



Methodology & Learning Report

Work package 2.1: Dynamic thermal rating of assets – Primary Transformers

May 2015

Contents

1 Executive Summary

This methodology and learning report covers the work that has been undertaken under work package 2.1 on the dynamic thermal rating of primary transformers within the project trial areas of St Andrews and Whitchurch. Much of the work was undertaken in conjunction with DNV GL. The remit given to DNV GL was broadly across 3 objectives; Condition assessment of the transformers; Determine suitability for dynamic loading; and Make recommendations for a solution.

DNV GL initially carried out a data gathering exercise on the transformers followed by comprehensive site surveys that included thermal imaging, partial discharge measurement and oil sampling. The results allowed DNV GL to conclude that the transformers are suitable for careful loading above nameplate rating. DNV GL subsequently used their dynamic rating modelling tool to predict the capacity of the transformers under historic loading conditions and future loading scenarios. They further recommended the benefits that a real time thermal rating (RTTR) system could have in allowing the ultimate capacity of transformers to be realised.

Further analysis by SP Energy Networks (SPEN) has revealed that associated assets in the trial areas effectively limit the increase in capacity available from the transformers to well below the level that would require a closed loop RTTR system to be deployed. We believe this will apply to most areas of our network and have therefore developed a technique that allows us to assign "enhanced" ratings to primary transformers using a modelling technique based on historical load profile and ambient temperature data. This technique has already been adopted and is being applied in business as usual and has enabled us to defer reinforcement projects at a number of locations resulting in savings for our customers. We believe that this is a technique that is highly replicable in other DNO's.

2 Background

Present industry best-practice revolves around the use of fixed equipment ratings based on conservative seasonal conditions. Improved thermal management of network assets using real-time dynamic ratings can help to release additional network capacity, potentially avoiding triggering of unnecessary network reinforcement for relatively small levels of demand growth.

National standards assign different thermal ratings to network assets during each operating scenario, taking into account both the representative equipment loading and typical ambient conditions. DNOs have typically used two approaches in the past. The first is to "weather correct" the demand to an Average Cold Spell (ACS) reference temperature, and then to use the rating of plant at this reference temperature. It is then assumed that if it is colder, demand will increase but at a slower rate than the increase in asset rating due to lower ambient temperature. This approach is difficult to apply to summer loadings and many Network Groups do not exhibit strong temperature dependency of demand. Often, the critical case is under planned outage conditions, and these occur in the summer. The present P2/6 default of summer peak load is 67% of winter peak which is not representative enough for current or future networks.

The second is to modify the rating to suit the season that the demand occurs within. Up to four seasons have been typical. Some DNOs have interpolated published ratings to give individual monthly ratings. For example, the autumn rating for overhead lines includes November and demand often increases significantly towards the end of this month and can cause ER P2/6 non-compliance on paper.

Both of these existing approaches use a fixed rating. This allows the network capacity to be calculated and compared to the network demand for the scenario being assessed. The use of generic asset ratings that do not consider the actual thermal conditions experienced can lead to unnecessary triggering of network reinforcements and corrective measures to reduce load due to indications that thermal headroom is exhausted.

3 Details of the work carried out

3.1 Project location

Transformers were selected from each of the 3 trial areas to include a degree of climatic variation. 8 Primary transformers within the 3 trial areas were selected in order to obtain as diverse a range of ratings, ages and manufacturers as practicable. The sites chosen were as follows: -

Cupar Primary (2 transformers)

St Andrews Primary (2 transformers)

Yockings Gate Primary

Liverpool Rd Primary

Whitchurch Primary

Ruabon Primary

Nameplate details of the transformers at these sites are included in Appendix 1.

3.2 Initial Proposed Methodology

Through a competitive tendering exercise SPEN selected DNV GL to assist in this work package. The previous experience of DNV GL on the dynamic rating of assets was a significant factor in their selection. The remit for DNV GL was split into 3 subtasks.

3.2.1 Subtask 1: Asset condition assessment

Description: Complete a detailed condition assessment of the 8 primary transformers and any assets directly involved with a potential transformer RTTR system. The primary transformer details are found in Appendix 1.

Criteria: Provide background information, justification and approach for all testing methods chosen to produce a detailed condition assessment of each transformer.
Provide information and an approach for any tests or software that can assess the limitations introduced by other assets (i.e. cables, tap changers) on a RTTR system.
Detail any work that will involve SPEN staff.
Provide network requirements and timescales for the tests to be completed.
Complete all stated tests.

3.2.2 Subtask 2: Assessment of the RTTR capability of assets

Description: Using the data gathered in work package 1 (and from other sources), provide an evaluation with reasoning on the asset capability of adopting an RTTR system at each primary substation.

Criteria: Provide a predicted RTTR profile for each transformer, with appropriate reasoning.
Give an estimation on the predicted rating uplift period for each transformer, with appropriate reasoning.
Provide details on what is the maximum loading increase that each transformer can safely achieve, referring to the transformers end of life
Give details on the factors that may limit the effectiveness of an RTTR system and suggest feasible options to reduce these limitations.
Give reasoning on whether the installation of an RTTR system is worthwhile from an engineering and business perspective.

3.2.3 Subtask 3: Recommendations for adopting an RTTR system

Description: If a RTTR system is considered a feasible option, give recommendations on future steps regarding the criteria listed below.

Criteria: Provide details on the equipment that would be needed to be installed to achieve RTTR.
Recommend steps that would be involved in the delivery of an RTTR system.
Describe the approach for the integration of output information into our operational systems.
Provide wider recommendations into how the findings of the asset health assessments and the recommendations for the implementation of and RTTR system can apply to all SPEN primary transformers.

3.3 Asset Condition Assessment

In the context of the RTTR project DNV GL assessed the condition of each transformer and estimated its remaining life. The following activities were performed:

- collection and analysis of the available information
- detailed visual inspection
- thermo-graphic inspection
- online partial discharge measurement
- oil analysis (dissolved gasses, quality, corrosiveness, furanic compounds)
- estimation of the remaining life on the basis of:
    - furanic compounds in the oil
    - dynamic loading-guide calculation.

3.3 Asset Condition Assessment [continued]

The results of the condition assessment were provided in a Condition Assessment Report included in Appendix 2. The conclusions can be summarised as follows: -

1) The estimated remaining lifetime of all 8 transformers that were part of the condition assessment is over 25 years.
2) The observations during the visual inspections, thermo-graphic surveys (IR), online partial discharge measurements (PD) and oil analyses can be summarized as follows:

Transformer	Visual	PD	IR	Oil
St. Andrews T1	Rust	OK	OK	OK
St. Andrews T2	Rust	OK	Hotspot on 33 kV terminal	OK
Cupar T1	Rust, sweating	OK	OK	OK
Cupar T2	Rust, sweating	OK	OK	OK
Ruabon T1	OK	Corona discharge in air	Peculiar temperature profile on radiators	Free water
Whitchurch T1	OK	OK	Hotspot on 33 kV-disconnectors	Free water PD-activity
Yockings Gate T1	Leaking cable box	OK	OK	OK
Liverpool Rd. T1	Sweating	OK	OK	PD-activity

Subject to certain mitigative measures to be implemented on Ruabon T1 and Whitchurch T1, DNV GL qualified the following six transformers as being suitable for operating under overloading conditions under careful dynamic loading:

- St. Andrews T1 and T2
- Cupar T1 and T2
- Yockings Gate T1
- Liverpool Road T1.

3.4 Assessment of the RTTR Capability of Assets

DNV GL assessed the thermal behaviour of these transformers using the loading guide as a calculation model with the measured ambient temperature and load profiles. In particular, the following activities were performed:

- Collection and analysis of the available information
- Development of the thermal model
- Creating future load patterns, based on actual load patterns to simulate and verify a safe increase
  - by 8%, 10% and 12% of the actual load profiles
  - up to a peak at nameplate rating
  - up to an 8%, 10% and 12% on top of a peak at nameplate rating
  - up to a 15 years, 40 years and 60 years electrical lifetime
- Creating future load patterns, based on actual load patterns and different levels of load increase due to:
  - Charging of electrical vehicles
  - Generated solar energy
  - Installation of electrical heating.

DNV GL presented their findings in their report 'Prospects of applying RTTR to distribution transformers' included in Appendix 3. From the analysis presented in this report, the following conclusions can be drawn:

1. All transformers are currently thermally low loaded
2. The temperature of the transformers is rather constant. This is due to the fact that the loading is highest in the winter when the ambient temperature is lowest and vice versa in the summer
3. Peak loadings can be increased above nameplate rating by 30-45% whilst maintaining an expected electrical lifetime of 40 years, given the situation in the current evaluation period and the parameters used in the model are sufficiently representative for the different transformers
4. With respect to integrating future loads coming from solar energy, electrical heating, electrical vehicles, etc., up to 15 MVA of additional peak loading can be allowed on top of the current load profiles
5. Close to the thermal limit, the ageing rate of the transformer increases rapidly and thus care should be taken when operating close to the thermal limit. The life time reduction increases significantly for hot spot temperatures close to and above 120 ˚C and considering the possible impact of the hot spot factor on the hot spot temperature, it is advised to limit the hot spot temperature to 110 ˚C.
6. Using RTTR, full transparency regarding the decision to increase the loading can be provided to regulators and auditors
7. RTTR enhances confidence in the network operation and supports timely actions like load-shedding
8. Knowledge about possible loading capabilities of transformers, gathered with an RTTR system, can be used as input for short and long-term plans for the management of the SPEN network
9. Implementing RTTR can result in significant higher benefits if compared to the necessary implementation costs and additional costs for losses

3.5 Recommendations for adopting an RTTR system

DNV GL made the following recommendations: -

1. Due to the cyclic load pattern, the peak loading of the transformer can easily exceed the name plate rating without resulting in higher than nominal loss of life. To ensure the loss of life remains close to but below the nominal value, it is recommended to install a monitoring and real-time thermal rating system. Moreover, it is advised to take extra oil-samples during the verification tests after implementing RTTR to ensure no load-related internal defects become active.
2. From an efficiency and cost-reduction point-of-view, groups of similar transformers can be defined e.g. based on rating, manufacturer, age, location, etc. To accommodate thermal rating on such group only one thermal model is required reducing cost for software development and hardware. Investments cost can be divided over several transformers within each group.
3. It is recommended to perform a heat run test. Preferably this test needs to be done for each transformer to know its specific hotspots. To reduce costs, it could be decided to perform such a test once for each group of similar transformers, with the loss of a small amount of accuracy.
4. It is recommended to limit the hot spot temperature to 110 ˚C to account for possible deviations of the parameters given in the IEC used in the models from the actual values.

3.6 Experimental validation of modelled results

In order to validate the results of the modelling, experiments were undertaken.

Initially the winding temperature indication / alarm / trip device on Liverpool Rd primary transformer was replaced with an electronic equivalent with remote data logging on iHost.

UoS prepared a technical note based on initial measurements of transformer top oil temperature at Liverpool Road primary under normal loading conditions (Appendix 4). Key learning outcomes are:

- The model is somewhat effective in reproducing the general behaviour of oil temperature in response to changes in load and ambient temperature
- For the conditions assessed, the model significantly overestimates the oil and hotspot temperatures at any given moment, by an average of 7.5°C and 6°C respectively
- There are strong indications that the overestimate of both the oil and hotspot temperatures becomes larger as the transformer load increases
- The model also overestimates the daily maximum temperatures by an average of 7°C.
- When planning a higher-load experiment with the model, it is therefore not necessary to allow a margin of error in the expected transformer temperatures; indeed it is likely to be possible to run at higher loads than suggested by the model
- The model has not been tested at high ambient temperatures or high loads: more data on performance above two thirds of nameplate rating and at warmer times of year is needed.
- Following the planned tests at Liverpool Road, further investigation of the model's parameters should be undertaken to determine whether a more accurate prediction of transformer behaviour can be achieved.
- Manufacturers' thermal test data for the transformer or for one of a similar design may help to improve the accuracy of the model.

In relation to the measurement of ambient temperature, the following learning point is noted:

For the purposes of modelling transformer thermal behaviour, ambient temperature data from either Whitchurch weather station appears suitable. This suggests that fewer weather stations could be installed in future area deployments.

4 The outcomes of the work

4.1 St Andrews trial area

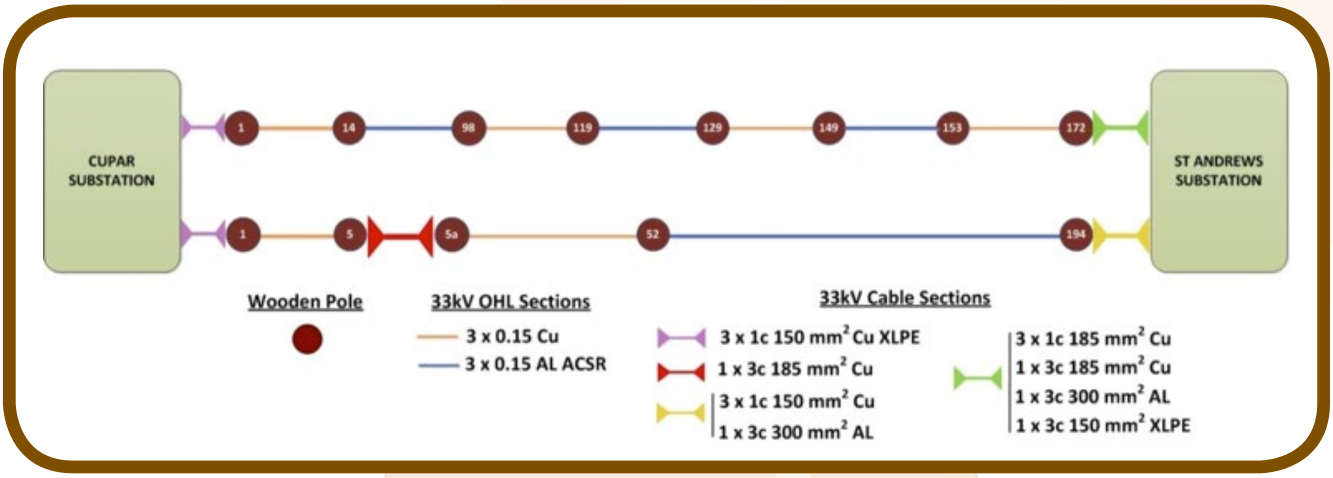
As explained above, in their study DNV GL developed a thermal model for the transformers at St Andrews primary substation and created future load patterns, based on actual load patterns to simulate and verify a safe increase in loading.

The results of this modelling are documented in the DNV GL report 'Prospects of Applying RTTR to Distribution Transformers' included as Appendix 3.

The study concluded that peak loadings can be increased above nameplate rating by 30% while maintaining an expected technical lifetime of 40 years.

A study of the other associated assets considered

- The 33kV cabling and OHL in the circuits supplying the transformers. The make-up of the circuits are shown below. The ratings have been checked against the ratings in the SPEN Equipment Ratings document ESDD 02 007. The lowest ratings are associated with certain cable sections which have a winter cyclic rating of 24MVA.



- The 11kV transformer tails
  Transformer tails are 2x500mmCu (or imperial equivalent).
- The 11kV switchboard
  The incoming circuit breakers are Hawkgas 12 rated at 1250A with 1200A CT's.

This study concluded that capacity of associated assets effectively limit the peak loading on the transformers to 24MVA, equivalent to a 14% uplift on peak loading. The long term development statement (LTDS) will be amended to include the new firm capacity.

The calculation of the transformers enhanced rating requires their typical load profile to be taken into account. This profile could change in the future due to the impact of changing loads arising from, for example, low carbon technology or new connections. The Flexible Networks project has developed a tool which allows designers to calculate the enhanced rating of primary transformers, knowing the characteristics of the transformers, the ambient temperature, and their load profile. This enables the enhanced rating of the transformers to be recalculated should there be a significant change in the load profile in future.

In order to maximise the potential of the transformers to achieve their theoretical remaining life it was necessary to refurbish the transformers including the installation of new cooler banks. This was undertaken in March 2015. Although this work is not required to achieve the additional capacity it is necessary to provide assurance that the capacity can be maintained over their remaining life.

4.2 Whitchurch Trial Area

The Whitchurch group comprises of 3 single transformer primary substations : - Whitchurch, Yockings Gate, and Liverpool Rd. Intact capacity of the Whitchurch group is listed in the LTDS as 22.5MVA, (3x7.5MVA)

The theoretical maximum group capacity is listed in the LTDS as 20MVA and is based on a single transformer outage with all three transformers having a cyclic rating of 130% or 10MVA. This theoretical maximum would only be achieved if the demand in the network were perfectly balanced. Therefore modelling was undertaken by TNEI to take into account actual network conditions.

The network was modelled with actual demand figures from IHOST on 07/11/2013 17.30 (highest demand of an average winter day). This was then scaled to meet the group maximum demand listed in the LTDS. The sum of the individual substation peaks is virtually identical to the group peak.

The network was assessed under N-1 conditions, reconfigured and demand uniformly grown across network until a thermal (transformer or circuit) or voltage limitation was identified.

Under loss of a transformer, reconfiguration was considered to be by opening the feeder breakers and resupplying the feeder from its remote end.

In general feeders are resupplied by other transformers within the group. The exceptions are four feeders out of Whitchurch – it was assumed that these would be resupplied by their remote ends (Ellsemere, Overton, Wrenbury Frith, Newhall).

The St Ivel feeder out of Yockings Gate was not resupplied from Prees – rather it was assumed that this would be resupplied through the Yockings Gate busbars, or from Liverpool Road.

4.2 Whitchurch Trial Area [continued]

The results of the modelling are sumarised in the table below.

Network demand scaling factor	Study Condition		Equivallent group loading under Intact	N-1 flow through transformers	Whitchurch 33/11 7.5/10MVA 10 / 10 11 / 11	Liverpool Road 33/11 7.5MVA 7.5 / 10 8.25 / 11	Yockings Gate 33/11 7.5MVA 7.5 / 10 8.25 / 11	Transformer Type Existing Rating (Intact/N-1) Enhanced Rating (Intact/N-1)
1.000	Intact	Unscaled BASECASE demand	14.700	-	6.969	4.465	3.266	
1.180	N-1 LIV RD	Existing - limited by feeder thermal issues	17.346	17.72	8.669	-	9.046	Thermal overload on HV feeder near Girls High School
1.300	N-1 LIV RD	Transformer ratings enhanced by 10%	19.110	19.64	11.01	-	8.634	Limitation is Whitchurch transformer
		Capacity release through Transformer enhanced rating	1.764	10.2%				
1.290	N-1 YOCK	Existing	18.963	19.37	10.04	9.332	-	Limitation is Whitchurch transformer
1.410	N-1 YOCK	Transformer ratings enhanced by 10%	20.727	21.29	11.05	10.246	-	Limitation is still Whitchurch transformer
		Capacity release through Transformer enhanced rating	1.764	9.3%				
1.660	N-1 WHIT	Existing	24.402	17.38	-	10.024	7.352	Limitation is Liverpool Rd transformer
1.815	N-1 WHIT	Transformer ratings enhanced by 10%	26.681	19.12	-	11.022	8.095	Limitation is still Liverpool Rd transformer
		Capacity release through Transformer enhanced rating	2.279	9.3%	(Under N-1 configuration some feeders are supplied by remote ends, consequently group demand had to be increased more before issues were identified. This level of group demand would be expected to be limited under intact conditions)			

For all three transformer outage conditions studied, enhancing the rating of the transformer by 10% released significant amounts of capacity.

For outage of the Liverpool Road transformer, the first limitation identified was a thermal overload on an HV feeder near the Girls High School. Although some demand on this feeder could be moved by operating the tele-controlled switching points to move the normally open point from Bargates to Green End Arcade. The loading on the Whitchurch transformer would increase to its maximum continuous ONAF rating of 10MVA. For the purposes of this analysis, this is considered to be the existing limitation of the group.

Enhancing the thermal rating of the Whitchurch transformer was able to release approximately 10% of existing firm capacity as it enables the above reconfiguration which alleviates the HV feeder constraint. The next constraint was the enhanced thermal rating of the Whitchurch transformer.

Firm capacity was considered to increase from 17.34MVA to 19.11MVA (10.2%)

For outages of either of the Whitchurch or Yockings Gate transformers, the HV feeder network was not found to limit the capacity. The first limitation was the cyclic rating of other transformers in the group.

Under N-1 of the Whitchurch transformer, some feeders were supplied by remote ends (Ellsemere, Overton, Wrenbury Frith, Newhall). Consequently the group demand is lower under these conditions and this is therefore not expected to be the limiting contingency for the group.

Results also indicated that under N-1 conditions, loading on Yockings Gate could be managed so that it doesn't exceed 10MVA (and therefore does not require enhanced rating).

As a consequence of the above assessment the firm capacity of the Whitchurch group in the LTDS will be increased by 10%.

4.3 Business as Usual

Having reviewed all of the learning from this work package we have concluded that it is not necessary to implement a closed loop real time thermal rating system as recommended by DNV GL in order to get the benefit of additional capacity above nameplate that is available from primary transformers. The explanation for this decision is as follows.

The results of 2 separate studies within the project have shown that, given the cyclic nature of our loads, it is possible to increase peak loading up to around 30% above nameplate rating. However In real networks there are usually associated assets such as cables and switchgear that restrict the potential peak loading below this level.

The Transformer Loading Tool developed under the project enables the individual historic loading profile and site specific ambient temperatures to be used to determine the 'Enhanced Rating' for a primary transformer.

We have taken the decision that where enhanced ratings are being implemented it is prudent to replace the existing winding temperature indicator (WTI) and its associated alarm and trip outputs with a modern electronic unit. The reasons for this are firstly because the transformer could be operating at a higher temperature it is important that the alarm and trip settings are accurate. Secondly, the new instrument provides an analogue output signal that enables the transformer temperature to be presented in real time on the operational network management system, and logged centrally for subsequent review. We have also commenced trials of an online dissolved gas analysis instrument to investigate whether this provides any useful data in relation to primary transformers subject to enhanced rating.

We have therefore developed the following methodology for the 'Enhanced Rating' of primary transformers: -

1. Carry out a desktop study of our reinforcement programme to identify primary transformers that are candidates for enhanced rating. That is where the typical level of enhanced rating that we expect would result in the deferment of traditional reinforcement.
2. Use the Transformer Loading Tool developed under the project to model the transformer using actual historic loading data and ambient temperature to give the potential enhanced rating of the transformer.
3. Examine associated network assets, typically cables, overhead lines, and switchgear for any limitations on capacity that they impose.
4. Therefore determine the resulting enhanced firm capacity of the substation or group and confirm that this is sufficient to defer conventional reinforcement.
5. Carry out a condition survey of the transformer including oil tests to verify that the transformer is suitable condition for enhanced rating. Undertake refurbishment where necessary and economically viable.
6. Retrofit an electronic winding temperature instrument with remote temperature data availability.
7. Revise the substation or group firm capacity stated within the LTDS.
8. At regular intervals,(e.g. annual or bi-annual) re-run the transformer model with updated loading data and review the transformer temperature data log.
9. Revise as necessary the firm capacity stated within the LTDS.

5 Business Case

The enhanced rating of primary transformers can facilitate the deferral of conventional reinforcement under different scenarios. Considering 2 typical applications: -

Deferral of 33kV Primary Substation Construction

In this scenario the existing primary substation is nearing capacity and is already equipped with transformers of around the standard maximum rating employed.

The lowest cost traditional method would be the provision of an additional primary substation including two new 33/11kV transformers, new 11kV switchgear, new 33 kV overhead line or underground cable, and extensive cable works to reconfigure the 11kV network. In our experience such projects take approximately 3 years to implement and the typical total cost is £6,200k.

In appropriate circumstances, enhanced rating of primary transformers can defer the requirement for conventional reinforcement. The duration of the deferral period will be dependent on the rate of load growth which is itself dependant on a number of factors including the future uptake of low carbon technology. We consider the technique to be applicable where a deferral period of at least 8 years can reasonably be expected based on a range of load growth scenarios.

Referring to our Cost Benefit Analysis (Appendix 5) the average cost of implementing enhanced transformer rating at a 2 transformer primary substation is estimated at £30k.

Therefore under this scenario an expenditure of £6,200k is expected to be deferred for a minimum period of 8 years for an expenditure of £30k.

Deferral of 33kV Transformer Reinforcement

In these circumstances a primary substation is nearing capacity, however the existing transformer(s) have a significantly lower rating that the present standard maximum rating employed.

The lowest cost traditional method would be the replacement of the transformer(s) with new units having a higher rating, together with associated civil works and any upgrading of cables required. The budget costs for a typical project are £300k per transformer.

In appropriate circumstances, enhanced rating of primary transformers can defer the requirement for conventional reinforcement. Again, the duration of the deferral period will be dependent on the rate of load growth and we consider the technique to be applicable where a deferral period of at least 8 years can reasonably be expected based on a range of load growth scenarios.

Referring to our Cost Benefit Analysis the average cost of implementing enhanced transformer rating is estimated at £15k per transformer.

Therefore under this scenario an expenditure of £300k is expected to be deferred for a minimum period of 8 years for an expenditure of £15k.

Under both of the above scenarios significant savings are achieved for our customers.

6 Conclusions

This work package has successfully facilitated the increase in firm capacity of the primary substations in the trial areas of St Andrews and Whitchurch, thereby contributing to the success criteria for the project.

Benefits from this work package are however much more wide ranging. Our knowledge of the thermal behaviour of primary transformers has been greatly enhanced. We have introduced the technique of enhanced ratings for primary transformers into our business as usual processes, and that has enabled us to defer reinforcement projects at a number of locations resulting in savings for our customers. We believe that this is a technique that is highly replicable in other DNO's.

7 List of Appendices

Appendix 1 – Nameplate Details of Transformers

Appendix 2 – Condition Assessment Report (DNV GL)

Appendix 3 – Prospects of applying RTTR to distribution transformers (DNV GL)

Appendix 4 – Experimental Validation Report

Appendix 5 – Cost Benefit Analysis