Report (updated)

Estimate of AC losses: Electricity Supply Tariff Area Analysis – CP5 proposal

Network Rail
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Issue Record

Issue	Date	Author	Amendment Summary
P01	August 12	KWM	Initial draft.
P02	August 12	KWM / SNP	Updates and incorporation of comments.
P03	August12	KWM	Added further updates.
P04	August 12	KWM / SNP	Added executive summary and incorporated comments.
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A01	August 12	KWM	For issue.
A02	August 12	KWM / SNP	Updated with NR Planning and Regulation comments.
A03	August 12	KWM	For issue.
A04	December 12	KWM	Incorporating regulators independent reviewers comments

Executive Summary

Train operators opting-in to the on-train metering billing system on the Network Rail AC electrification network are charged on the basis of their metered energy consumption plus a percentage uplift to account for electrical losses in the network.

Electrical losses consist of a combination of fixed and variable losses. The fixed losses are a constant and occur all the time the network is energised. The variable losses occur when current is flowing, predominantly as a result of trains drawing traction energy.

Network Rail completed studies in 2011 which estimated the average value of electrical losses to be in a range of 4% to 6%. For the billing purposes it set losses at 5% for the AC network, this was expressed as an uplift percentage of power used by the train. It was supported by the industry that the value would be set at 5% for the rest of Control Period 4 (CP4)[1].

As part of Periodic Review 2013 (PR13), Network Rail reviews the charges it levies on its customers. All final charges are developed in consultation with the industry and are audited and approved by the Office of Rail Regulation (ORR) as part of its periodic review. The PR13 determination will set out the proposed approach for developing the Electric Current for Traction (EC4T) charging framework for implementation from the start of the next Control Period, (CP5)[2].

This report will support Network Rail's work to develop the EC4T charges framework for CP5, and supersedes the previous version published for consultation in September 2012[3]. The key updates are:

- Remove modelling uplift.
- Re-calculation of fixed losses across the network.
- Apply a weighted AC average losses mark-up.

Since 2011, further studies have been commissioned by Network Rail to further understand the driver(s) of electrical losses on the AC network. It has been established that there are many variables that can contribute to electrical losses which make it difficult to scientifically calculate an absolute figure for losses on the AC network. Although in a commercial environment the appropriate value of losses should be scientifically based on the element of engineering judgement and probability regarding the many variable factors that can occur.

As part of the EC4T charging process the AC electrical network is divided into 18 Electricity Supply Tariff Areas, (ESTAs) for billing purposes. Network Rail's

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[1] This is the regulatory period from 1 April 2009 – 31 March 2014.

[2] This is the regulatory period from 1 April 2014 – 31 March 2019.

[3] Network Rail (September 2012) 'estimate of ac losses report', accessible here: http://www.networkrail.co.uk/publications/delivery-plans/control-period-5/periodic-review-2013/pr13-closed-consultations/

duty under its licence is to manage the network in an "*efficient and economical*" manner and has provided an indicative electrical range of losses across the entire AC ESTA network outlined in Table 2. The estimation of losses is a very complex issue and it has been a complex task to disaggregate the losses mark-up value over the 5 ranges, especially at the lower end, where less energy is utilised. We expect this issue to improve over CP5 as Network Rail and the industry's data on losses becomes more robust.

It should be noted that rather than take the direct average over the five ranges of MWh per STK results, a more accurate calculation is to take a national weighted average across the current 7,230 STK AC traction network.

MWh per STK	AC ESTAs	Total STK – km	I^2R energy loss range	Average Fixed energy loss	Median energy loss	Losses mark-up
0 – 100	D, F	633	1.2% - 1.4%	3.36%	4.66%	4.89%
100 – 200	A,B,C,E,I,J,N,S	2885	1.4% - 1.6%	2.56%	4.06%	4.23%
200 – 300	G,H,Q,V	1535	1.6% - 1.8%	2.02%	3.72%	3.86%
300 – 400	O,P,R	1516	1.8% - 2.0%	1.21%	3.11%	3.21%
400 – 500	T	661	2.0% - 2.2%	1.2%	3.30%	3.41%
					National Weighted Average	3.85%

Table 2:- Indicative AC Losses by ESTA

The national weighted average of the 5 ranking groups of MWh per Single Track Kilometre (STK) is 3.85%. This result supports the early 2011 estimate as an uplift percentage of power used by the train.

The electrification expansion outlined in DfT's High Level Output Specification (HLOS) for CP5 will add approximately 3,000 STKs to the existing AC network. Putting this plan into context will be equivalent to implementing a new electrified line from London to Edinburgh.

Over the last 22 years the AC network's energy consumption has expanded at an annual rate of 1.56%. It is almost certain that the planned electrification expansion programme will increase the average AC electrical loss during CP5. It is estimated that the average level of AC losses will rise by approximately a further 1% over CP5.

With the planned increase of AC electrification during CP5 and in order to provide certainty to train operators who wish to opt-in for on train metering and the ability to manage their EC4T bills, Network Rail will propose to set a single AC national weighted average mark-up of 3.85% for the whole of CP5.

Fixing the average level of electrical losses at 3.85% across the AC network for the duration of CP5 will also demonstrate a level of incentive to Network Rail to make the necessary efficiency improvements to match such a level of increase in demand never seen since the Victorian times. The current industry consultation on the proposed losses estimate / mark-up is seen by Network Rail as a 'starting point', and should be subject to review. Network Rail therefore considers that there may be merit in allowing the mark-up to be reopened in the light of significant new information.

1. Introduction

Network Rail, the infrastructure operator of the UK railway network, is responsible for managing two different types of electrical traction networks. This report will consider the level of electrical losses on the AC network operating at 25kV on the overhead line system. The dc networks electrical losses will be considered and discussed in further reports and studies, which are due to be published later in 2012.

The extrapolation process of the AC electrification losses has been closely aligned with the EC4T billing system, which splits the AC and dc networks into ESTAs.

This report has also been reviewed by the regulators independent reviewer Asset Management Consulting Limited (AMCL) on the engineering approach and robustness taken by Network Rail in determining its proposed estimate of the AC networks losses [9].

The output and analysis of this report will support Network Rail's EC4T consultation, which will consult on options for developing the EC4T charging framework for CP5, including the proposal for setting the appropriate percentage uplift for AC electrical losses.

1.1 Aim and Purpose

This document is intended to support Network Rail's EC4T consultation. It summarises the methodology used and the output enables the extrapolation of the AC losses across the entire network.

1.2 Scope

There are currently 20 ESTAs that capture the entire Network Rail network. 18 predominately feed the AC network with 2 feeding the dc network. There is a single ESTA capturing the entire southern dc network with the other dc area encompassing Mersey Rail, these 2 dc networks will not be assessed as part of this report.

This report will identify the existing geographic disaggregation of the total AC losses across the network. It will consider the new electrification over CP4 and CP5 and the effects it will have on total losses across the network.

1.3 Structure

The structure of the document is summarised below;

Section 1 - Introduction - sets out the aims, objectives and the scope of the document.

Section 2 - Background - contains references to historical descriptions of the network

Section 3 - Assumptions and Methodology - provides a brief outline of the methodology adopted and sets out the key assumptions we have made.

Section 4 - ESTA Analysis – details the extrapolation process across the present ESTA configuration.

Section 5 - CP5 future electrification – this section quantifies the scale of the new electrification plans and the effects it will have on electrical losses.

Section 6 - Conclusion - outlines the main conclusions of the report.

Section 7 - Recommendations - outlines the key recommendations with proposals to support the EC4T consultation.

Section 8 - Definition and abbreviations – lists the main definitions and abbreviations within the report.

Section 9 – References – lists the main references within the report.

2. Background

Train operators opting in to on-train metering in CP4 are charged on the basis of their metered consumption plus a fixed percentage uplift to account for losses in the system across the appropriate ESTA. As a result it is commercially necessary to be able to model the network losses under normal timetable operation to confidently determine the losses uplift that should be applied to the energy metered by the train operators within a particular ESTA.

In addition, Network Rail has a duty under its licence to manage the network in an "*efficient and economical manner*" and therefore an inherent duty to demonstrate that electrical losses occurring on the traction system are reduced where economically viable; this requires Network Rail to accurately quantify electrical losses.

Electrical losses consist of a combination of fixed and variable losses. The fixed losses are constant and occur all the time the network is energised. The variable losses occur when current is flowing predominantly as a result of trains drawing traction energy.

Network Rail operates a number of computer models to calculate the energy consumed by trains operating on the AC system. These models are designed to take into account the many variables that influence this energy consumption (e.g. train design, driving style, weather, rail wear, etc) and the consequent variability of losses.

Network Rail has used cross industry support to progress further studies on this subject and to this end has commissioned a project, *"Measurement of Electrification System Losses"* to carry out a series of on-track measurements for comparison with modelled analysis of a similar network. To validate this modelling, Network Rail contracted with a number of third parties to carry out similar modelling exercises. [1]

This report will conclude on and make recommendations regarding:

a) The improvement of the estimation of losses on the system;
b) the extrapolation of AC losses across each ESTA; and
c) the potential economically efficient level of AC losses that could be achieved during CP5.

2.1 Network Rail AC Electrification Review – NR-EP-EC4T-2010-001

Network Rail completed studies earlier in 2011 which calculated the value of losses to be 5% for the AC network. This was expressed as an uplift percentage of the power used by the train. The Network Rail report [2] concluded that 5% is considered the best estimate for traction losses based on our understanding of loads and system configurations as applied to a 25 kV AC overhead electric system based on the following estimation.

Estimation of Overall Losses	
Factor	**Estimated Value**
Resistive Losses	3%
Leakage	1.2%
Commercial	Up to 1.5%
Power Quality Equipment	0.53%
Adjustment for BT system	Up to 1.7%
Total	**4% to 6%**

3. Assumptions / Methodology

We have established that EC4T losses are a combination of fixed and variable losses across the AC network.

Variable losses (I^2R) are a multiple of the network impedance and the square of the load current and have been modelled over a 24-hour period using the 2015 ECML timetable. [4]

The AC network's fixed losses have been established using the annual 2011 energy consumption report and extrapolating the fixed loss across each ESTA [3 and 6].

It has also been possible to establish a relationship between the energy consumed (MWh) to the length of the feeding area (STK). This relationship enabled the summation of the variable and fixed losses for each GSP and therefore extrapolated across each of the 18 AC ESTAs.

In estimating the extrapolation of the total AC losses across the 18 ESTAs the following key assumptions have been made:-

1. The train simulation modelling package (Vision / Oslo) has been validated during Stage 1 of the project [1]. Due to the variable factors influencing losses [5] it has always been difficult to align real time data with modelled data. In the 2013 annual losses review, real time data from ESTA H may be used to further validate the ac losses.
2. No stabling loads in depots or sidings have been included in our modelling assumptions.
3. Using the Balancing Settlement Metering Code we have assumed

metering accuracy at the Network Rail GSPs will all operate to Code of Practice 1, (CoP). We have assumed the metering accuracy of +/- 1% will have a net effect on losses.

4. All on-train metering data will be within the metering tolerances specified in EN 50463[4]. We have assumed the AC metering accuracy of +/- 1.5% will have a net effect on losses.
5. The regenerative braking aspect within our simulation model has assumed a zero net impact on electrical losses. To illustrate this, if the figures set out in this report were to be applied in CP4 the losses mark-up would need to be increased to take account of the fact that the CP4 approach applies the losses mark-up to metered consumption net of regenerative braking. For example, if 18% of energy is regenerated, to convert the average 3.85% 'gross' losses mark-up we are proposing for the ac network, the following calculation is needed to establish the actual mark-up to apply:

   3.85% / 0.82 = 4.69%
6. We have not accounted for any system errors with the On-Train Metering (OTM).
7. We have assumed all energy consumed with our models is related to traction power.
8. All booster transformers in the calculation are rated at 290kVA with a fixed loss of 150 Watts as per the manufactures specification.
9. All autotransformers in the calculation are rated at 15MVA with a fixed loss of 6.5kW outlined in the Network Rail standards for autotransformers.
10. In all areas we have assumed two insulators are housed on every support structure with a span length between supports of 40m. It is difficult to quantify the amount of insulators across the network due to the different overhead line supports and feeding arrangements but we believe this assumption may be a conservative estimate.
11. The ratio of installed polymeric against ceramic insulators is assumed to be 50%. In order to quantify this assumption the local Route Asset Managers (E&P) have been requested to confirm / advise on this ratio. The information will be updated in the annual review.
12. UK climate is changeable over the 4 seasons. The UK receives a considerable amount of rainfall and precipitation from the fog and snow. We have demonstrated via our insulator studies the effects that wet conditions have over leakage losses. Using the data from various sources we have calculated a wet to dry annual ratio of 37% (i.e. in a 24-hour period, the insulators will be wet for 8.88 hours).

4. ESTA analysis

Currently within Network Rail's network there are approximately 123 GSPs;

[4] Euro norm 50463 sets out the European standards for on-train metering equipment.

approximately 79 are related to the AC network. The GSP is the location of the transformation of transmission voltages that are required for the power to feed the AC traction network. These GSP locations also house the settlement metering devices that support the EC4T billing process

Several GSPs are then grouped into 18 ESTAs for billing purposes. We have established that electrification traction system losses are made up of a combination of fixed and variable losses across the network. As part of the metered billing process, the energy consumed by the train operators is uplifted by a percentage to account for the electrification traction system losses.

Each ESTA is designated with an alphabetic code where each GSPs traction load feeds a section of railway and has a distance measured in STK, therefore grouping the relevant GSPs to make up the ESTAs.

Of the 18 ESTAs, there are 3 which incorporate a billing system for dual voltages (i.e. AC and dc networks). In these 3 ESTAs, identified as ESTA, P, R & T, the proportion of AC load that feeds the dc network is excluded from this analysis.

The boundaries of the 18 ESTAs are split by an isolated / earthed section known as a neutral section [8].

The method in calculating the variable and fixed losses on the AC network are illustrated in the following sections 5.1 and 5.2 with the estimated extrapolation of the total AC loss across each ESTA identified in Table 2 in section 5.3.

4.1 Extrapolation of AC Variable (I^2R) losses

Traction modelling has been carried out to determine the level of resistive losses (I^2R) and energy consumption based on the IEP 2015 timetable capacity over a 24-hour weekday period for each electrically fed section (GSP) that forms the East Coast Main Line (ECML) including the branch lines on the electrical network.

As expected, the percentage of resistive losses varies across all of the modelled ECML and branch line GSPs. In order to establish a load / resistive loss relationship the data was re-formatted based on the present ESTA configurations. This presented a relationship between the cumulative energy supplied in the modelled ESTA along with the percentage of resistive loss.

Using the modelled data, the relevant ESTAs were then ranked in terms of ascending percentage resistive loss. It should be noted that the ranking aligned with the 2011 energy usage MWh per STK. This clearly demonstrated that the resistive losses predominately depend on the train service and the load demand [4]. This relationship is a result of the historical pattern of incremental reinforcement matching the gradual increase in load demand and maintaining a limited level of headroom. Initially, reinforcement to network capacity that was not matched by a similar increase in load demand would result in reduced losses, this reduction then being eroded as load demand matched the new network capacity.

The total length of the modelled ECML and branch lines is estimated at 2,220 STK. It captures 6 ESTAs and the area represents 29% of the total 25kV AC electrified network and includes a mixture of rail return, classic and autotransformer networks.

The ECML modelled area used over 12% of the total energy usage of the 25kV AC UK railway network during 2011; it therefore provided a sound basis for extrapolating the resistive losses results across the entire AC network as outlined in the column "*I^2R energy Loss range*" within Table 2.

4.2 Extrapolation of AC Fixed Losses

Fixed losses on the AC network arise from the current that flows on the network irrespective of the load demand due to primarily transformer magnetising and insulator leakage currents plus any power quality equipment connected to the Network Rail infrastructure (i.e. harmonic dampers, etc).

It is difficult to model and simulate such fixed losses therefore various studies were commissioned in order to calculate each component's electrical loss either via testing or using manufacturer data sheets [6].

To gather the data for each of the components' electrical losses, a spread sheet for each GSP was assembled, supported by the latest infrastructure operational documentation (i.e. Network Rail - Route isolation diagrams). This enabled the correct quantity of components to be assembled per GSP (i.e. quantity of insulators, transformers, harmonic dampers etc).

Using the 2011 electrical energy consumption for each GSP [3] it has been possible to extrapolate an average daily load (kWh) for each Network Rail GSP. By inserting the 2011 average daily loads into the spreadsheet, the estimated 24 hour fixed no load losses for each GSP can be estimated. Under the commissioned independent review a more accurate and robust method is rather than summating the GSP averages is to sum the kWh supplied and lost for each GSP through to the MWh per STK bandings. The revised average fixed no load loss per AC ESTA is estimated in the table below.

	MWh per STK	AC ESTA's	2011 Total kWh	Loss kWh	2011 Fixed Loss - Average
	0-100	D, F	187,754	6,311	3.36%
	100-200	A,B,C,E,I,J,N,S	1,299,283	33,300	2.56%
	200-300	G, H, Q, V	952,140	19,263	2.02%
	300-400	O, P, R	1,606,463	19,388	1.21%
	400-500	T	881,771	10,622	1.20%
				National Average	**2.07%**

Table 1:- Indicative Fixed AC losses by ESTA

4.3 Estimation of Total AC Losses

Due to the many variables that can contribute to electrical losses it is still not possible to scientifically calculate an absolute figure for an AC traction network loss. Although in a commercial environment the appropriate value of losses should be scientifically based on the element of engineering judgement and probability regarding the many variable factors that occur [5].

Network Rail's duty under its licence to manage the network in an "*efficient and economical manner*" has provided an indicative electrical range of losses across the entire AC ESTA network outlined in Table 2. The table has been produced by summating the range of variable (I^2R) loss and fixed loss with the final column providing a train 'losses mark-up' value for input into the metered billing process. It should be noted that rather than take the direct average over the five ranges of MWh per STK results, a more accurate calculation is to take a national weighted average across the current 7,230 STK AC traction network. The weighted average losses mark-up of 3.85%, is broadly consistent with the early 2011 estimated AC 'losses mark-up' value.

MWh per STK	AC ESTAs	Total STK - km	I^2R energy loss range	Average Fixed energy loss	Median energy loss	Losses mark-up
0 – 100	D, F	633	1.2% - 1.4%	3.36%	4.66%	4.89%
100 – 200	A,B,C,E,I,J,N,S	2885	1.4% - 1.6%	2.56%	4.06%	4.23%
200 – 300	G,H,Q,V	1535	1.6% - 1.8%	2.02%	3.72%	3.86%
300 – 400	O,P,R	1516	1.8% - 2.0%	1.21%	3.11%	3.21%
400 – 500	T	661	2.0% - 2.2%	1.2%	3.30%	3.41%
					National Weighted Average	3.85%

Table 2 :-Indicative AC Losses by ESTA

5. CP5 - Future electrification and losses

Under the current electrification enhancement works in CP4 and the proposed CP5 High level Output Specification (HLOS), the electrification network will undergo the greatest expansion of the electric network since the Victorian times.

The expansion programme will inevitably increase variable loss and fixed loss on the network. The AC electrification programmes recently announced will add approximately over 3,000 STK of electrified route(s) outlined as follows:-

- Great Western Main Line Electrification - > 1000 STK additional electrified route(s).
- Crossrail - > 250 STK additional electrified route(s).
- Northern Hub Electrification - > 500 STK additional electrified route(s).
- CP5 - HLOS - > 1000 STK additional electrified route(s).
- Edinburgh & Glasgow Improvement Program – > 300 STK additional electrified route(s).

The integration of the above electrification expansion programme into the current ESTA configuration network is still at the preliminary design stages. Works are ongoing but the changes will be significant through out CP5 and an outline paper will be produced during the early stages of 2013 and shared with key stakeholders.

The annual energy usage illustrated an average annual AC network increase of 1.56% over the past 22 years [3]. It is therefore certain that the planned electrification expansion will maintain this upward trend. Putting the CP5 expansion programme into context, it is equivalent to implementing a new electrified line from London to Edinburgh.

At this stage, the increase on the AC network losses due to an increased load demand and further electrification is difficult to quantify without the integration of the ESTA configuration network being complete. Although from the losses work completed to date in Section 5.3, a conservative estimate of the AC network's average losses increasing from 4% to 5% throughout CP5 would be a valid assumption.

6. Conclusion

The following can be concluded from this report:-

1. The disaggregation of losses per ESTA outlined in Section 4.3 provides a very useful picture / benchmark on how the losses vary across the AC network with load. The estimation of losses is a very complex issue and it

has been difficult to disaggregate the losses mark-up value over the 5 ranges, especially at the lower end of the ranges, were less energy is utilised. We expect this issue to improve over CP5 as Network Rail and the industry's asset data on losses becomes more robust.

2. The changes in the ratio of variable losses against fixed losses provides Network Rail with useful information for policy to be reviewed and set to ensure the infrastructure has the minimum set of fixed loss [7].
3. Integrating the outputs of Table 2, with section 4.3, into the current metered billing systems may not benefit train operators as ESTA boundaries and their configurations will change during CP5 thus Network Rail would not be supportive for using this as a means of EC4T billing purposes. The current industry consultation on the proposed losses weighted average estimate / mark up is seen by Network Rail as a 'starting point' and will be subject to annual review.

7. Recommendations

Recommendations from this report are as follows:-

1. The work undertaken to refine the AC network losses estimates are based on models, testing, component manufacturing data sheets and assumptions. Therefore parts of the analysis may be subjective but Network Rail has used an element of engineering judgement and probability in order to conclude its findings and this report will be used as the starting point.
2. It is recommended that validation work continues with an annual report released to all key stakeholders.
3. With the planned increase of AC electrification during CP5 and in order to provide certainty to train operators who wish to opt-in for on-train metering and the ability to manage their EC4T bills, we are proposing to set a single AC national weighted average mark-up of 3.85% for the whole of CP5. Given that the forecast increase in services will naturally increase the level of loss and NR believe that maintaining a constant mark up during CP5 demonstrates an increase in the efficient management of losses matching load growth. However, we consider that there may also be merit in allowing a reopener within CP5 should significant further information come to light.

8. Definitions and abbreviations

The following definitions and abbreviations are used within this report.

AC	Alternative current
CoP	Code of practice
CP	Control period
dc	Direct current
DfT	Department for transport
EC4T	Electric current for traction
ECML	East coast main line
ESTA	Electricity supply tariff area
GSP	Grid supply point
HLOS	High level output specification
MWh	Mega watt hours
NR	Network Rail
OTM	On-train metering
ORR	Office of rail regulation
STK	Single track kilometres

9. References

No	Title	Author	Ref	Date

1	Summary – Stage 1 Measurement of Electrification System Losses AC network.	Simon Polley	TPD-NST-021- LOSS-REP-0005	2011
2	Estimation of Electrical Losses on 25kV AC electrification systems	Robert Wilson	NR-EP-EC4T-2011-001	2011
3	Traction Related Energy Usage - 2011	Mark Donovan	TPD-CFG-006-ECNK-0001	2012
4	ECML 24 Hour Resistive Losses	Phillippe Belvir	TPD-NST-021-LOSS-REP-0006	2012
5	Factors Causing Variability of EC4T Load and Impact on Losses	Simon Polley	TPD-DGN-LOSS-REP-0007	2012
6	Fixed No Load Loss – ESTA analysis	Kevin Middleton	TPD-DGN-021-LOSS-REP-0008	2012
7	Review of AC Traction Energy Efficiency Proposals	Simon Polley	TPD-CFG-006-ECNK-REP-0002	2012
8	Network Rail – Electricity Supply Tariff Area	Alan Bullock	Version 2.3	2011
9	EC4T Transmission Losses (AC & DC) Estimate Review	AMCL	Final Report	2012