Future of the Electricity National Control Centre - Thermal Constraint

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nationalgridESO

Contents

Introduction

The electricity industry continues to change at an unprecedented pace and scale as we move to a more decarbonised and decentralised energy landscape. We have seen continuing closure of large fossil-fuelled generation directly connected to the transmission system. This has been replaced predominantly by renewable generation, most often wind and solar and often embedded within distribution networks. Coupled with this transformation in generation, regulators have introduced further drivers to encourage competition and so deliver greater consumer value. Also, we have seen an increase in the number of interconnectors with other transmission systems and so a greater market liquidity seen as increasingly variable levels of import and export of energy via these interconnectors.

As National Grid ESO drives towards our ambition of being able to operate a carbon free electricity system by 2025, these combinations of network and market changes are expected to continue. This huge rise in variability of energy flows has impacted the operations of our network and has led to new operability challenges we will identify and manage.

In July 2019, National Grid ESO published a document outlining the Future of the Electricity National Control Centre. Within this document, we identified all key operational challenges to examine them further in order to set out our proposals to address each within the RIIO-2 framework. These challenges were grouped into six key areas as shown below:

As System Operator, our vision is for a more flexible electricity system that makes the most economic and effective use of all available resources to meet the continuing needs of the electricity network.

This document represents the first chapter and considers in more detail the operability challenge that is Thermal constraint. It describes what a thermal constraint is, describes tools and techniques we utilise in the management and mitigation of thermal constraints and gives further examples of recent operability challenges thermal constraints have created by considering case studies. Finally, we articulate some potential future operability challenges that may give rise to thermal constraint.

We're keen to hear your views on what we have shared in this publication. Your feedback will help us to continue developing our real-time network analysis and constraint management approach and is important in directing our future business plans for RIIO-2. Please let us know what you think of our publication at: **.Box. ENCCEnquiries@nationalgrid.com**

Thermal Constraint explained

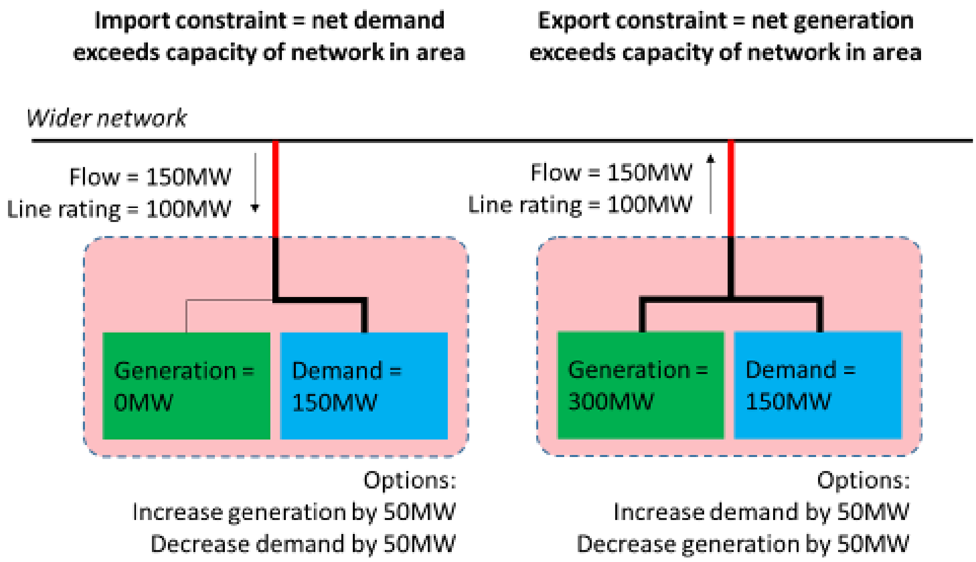
Each piece of equipment on the electricity network has a physical limit as to the amount of power it can withstand. With regards to thermal constraint this limit comes from the fact that as power flows through cables and wires it generates heat, due to the resistance of the metals from which the conductor is made. All assets on the transmission network have a rated thermal capacity specified in Mega-Watts (MW) or Mega-Volt Amp (MVA). As the ESO we need to manage the flows on the transmission network so that no piece of equipment is over heated.

The overheating of equipment leads to equipment failure, or for overhead lines the conductors will expand with the heat and potentially sag lower to the ground which may infringe the safety clearance distances and increase the risk of damage to equipment and property.

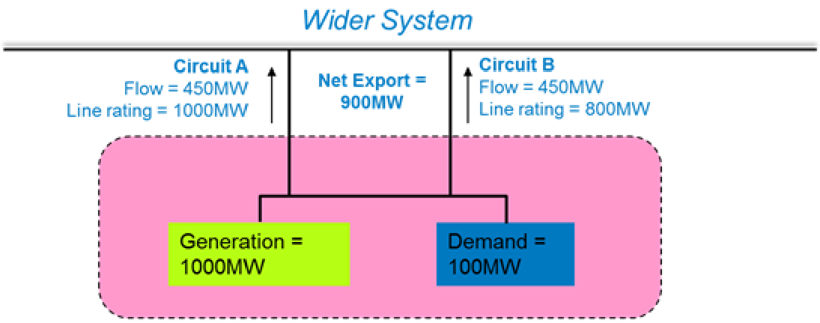
Thermal ratings are provided by the Transmission Owner (TO) to the System Operator as a means of defining the limit to which we may operate their assets. Thermal ratings of conductors consist of a pre and post-fault continuous value and often a range of short-term post fault ratings which although higher can only be utilised for a short duration. As the System Operator, we are obligated within our Transmission Licence, through the Security and Quality of Supply Standards to operate the system in a manner such that there shall not be any unacceptable overloading of any primary transmission equipment under normal operating conditions and post-fault following any credible transmission equipment fault events. This definition caters for the use of short-term ratings greater than the post fault continuous value as is often the case for overhead line circuits. Other primary transmission assets such as Super Grid Transformers are designed to operate at higher temperatures of up to 125 centigrade, beyond which the asset's integrity could be compromised leading to significant damage and risk of catastrophic failure as well as potential danger to life.

We meet our licence obligation, in control room timescales, by controlling thermal loading of transmission assets in real time operation. We do this by setting boundary flow limits across identified areas of network constraint and so manage thermal import and export constraints. We take actions in real time to avoid exceeding operating limits of transmission assets where the generation background and demand pattern mean that limits would otherwise be exceeded.

A simple example of thermal constraints showing the difference between import and export constraints on a transmission network is illustrated below:



In real time, we exploit the thermal capacity of transmission assets to avoid unacceptable overloads following transmission faults to maximise MW power transfers across constraint boundaries. We achieve this by limiting transmission equipment loading to 84% of their continuous rating under normal conditions to allow for enhanced short-term rating capacity we then utilise after a fault has occurred. The post fault short-term ratings, which are typically available for 10 or 20 minutes, allow our control engineers to take actions in real time to reduce the flow on the heavily loaded assets after a fault has occurred without exceeding the maximum operating temperature of the circuit, as illustrated in the following scenario. The benefit of this is that we can allow more power to flow pre-fault (i.e. most of the time) as we know we can take action within 10 or 20mins post fault.

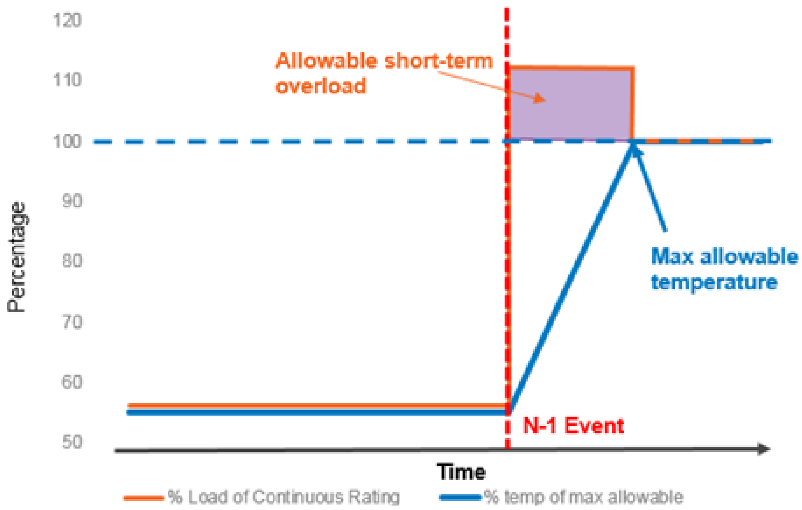


Normal Conditions
No unacceptable loading

N-1 contingency condition (Circuit B fault):
Circuit A flow = 900MW (continuous line rating = 1000MW)
No unacceptable loading

N-1 contingency condition (Circuit A fault):
Circuit B flow = 900MW (continuous line rating = 800MW, short-term 20 minute rating=900MW)
No unacceptable loading if:
Generation reduced by 100MW or demand raised by 100MW within 20 minutes else shutdown Export group

In the above example of a thermal export constraint, the worst N-1 event for thermal loading is the fault of circuit A, where Circuit B is loaded to about 112% of its continuous rating of 800MW. However, as the pre-fault loading is low, at 56%, the 900MW overload can be sustained for 20 minutes during which time, generation within the group may be sufficiently curtailed. The following diagram shows how the short-term overload can be sustained without overheating the circuit. In real time, ENCC control engineers would operate the transmission network within the constraint limit of 900MW.



An example of a ratings schedule below illustrates how post fault short-term ratings of 6 hours, 20 minutes, 10 minutes, 5 minutes and 3-minute ratings can be used to efficiently manage thermal loading of transmission assets in real time operation. Short term ratings of 20 minutes and 10 minutes allow for the ability to take manual generation drop actions postfault, whilst the 5 minute and 3-minute ratings are managed by utilising automatic generation inter-tripping. In this example the 6-hour ratings on the schedule for this asset equal the post fault continuous rating of the asset. A similar connection using an underground high voltage cable would benefit from a larger pre-fault rating of 95% and a larger 6-hour short term rating.

	Pre-fault Loading Winter			**Postfault Loading Winter**	**Pre-fault Loading Summer**			**Postfault Loading Summer**
	Winter %	MVA Rating	Limit	Postfault MVA	Summer %	MVA Rating	Limit	Postfault MVA
Pre-Fault load	84		OHL	1847	84		OHL	1605
Post-Fault load	100	2199	OHL	2199	100	1911	OHL	1911
6-hour rating	84	1847	OHL	2199	84	1605	OHL	1911
20 min rating	84	1847	OHL	2369	84	1605	OHL	2043
10 min rating	84	1847	OHL	2644	84	1605	OHL	2266
5 min rating	84	1847	OHL	3149	84	1605	OHL	2678
3 min rating	84	1847	OHL	3737	84	1605	OHL	3158

Figure 1: Example Winter and Summer ratings schedule for a 400kV Overhead Line (OHL) asset

In the table above also note that due to the difference in ambient temperatures, winter season ratings are higher than ratings in a summer season for the same asset. Spring and autumn ratings for the same asset are higher than summer ratings, although they will be lower than winter ratings.

Techniques for Managing Thermal Constraint

Our planning department works closely with Transmission Owners (TOs) from Year Ahead to Day Ahead timescales to build an operational plan to manage the number and location of outages on the network at any given time to best optimise the use of the network and minimise constraints.

In control room timescales, we receive the operational plan at day ahead and our control room strategy engineers then optimise using offline power flow analysis tool in intraday timescales to identify further opportunities for network optimisation. The operational plan is updated with latest demand forecast figures, latest known generation pattern and system outages including short term changes that may have occurred in control timescales. A range of offline scenarios are considered to ascertain thermal constraint limits against a background of changing demand profiles and differing renewable energy generation levels. These offline power flow tools are used to both assess network security and to predict system power flows enabling the ENCC to develop a short-term strategy to operate the electricity system as efficiently as possible whilst complying with SQSS and Grid Code.

Detailed system operational plans (SOPS) are developed for several set cardinal points across the day. Electricity demand goes up and down during a day depending on how much energy people, businesses and industries are using at that moment in time. As this electricity demand goes up and down, we get characteristic peaks and troughs, with some of these peaks and troughs appearing every single day at similar times. These peaks and troughs form the cardinal points we forecast demand for and use for the production of system operational plans. SOPs take into account both transmission network and energy requirements for the time periods down to 4 hours ahead of real time and looking out to the next 24 hours. These SOPS are updated and refined on a rolling basis with latest demand and generation data until they are made Final System Operating Plans at 4 hours ahead of real time. These final SOPS are adopted by the real-time despatch engineers to deliver and manage any further short-term changes.

Our real-time transmission despatch engineers are responsible for managing our business interface with the Transmission Owners, Distribution Network Operators (DNOs) and Offshore Transmission Owners (OFTOs), and other directly connected users. They will reassess plans to further refine the final system operating plans to accommodate latest system changes which may include asset faults, overrunning system outages and short-term outage requests in real timescales and the latest generation and demand profiles. The transmission despatch team, will continuously review and re-optimise the operational plan before delivering it in real time by:

- Instructing network reconfigurations through different running arrangements at substations; altering set points on series compensation devices and HVDC circuits to redirect flows to parts of the network with capacity,
- Utilising short-term circuit enhancements temporarily increasing the capacity of the network to allow additional power to flow for a predetermined period, or under specific weather conditions where we may be able to utilise Meteorology Office Rating Enhancements (this amends the thermal ratings on equipment based on the short-term weather forecasts).
- Arming Operational Tripping Schemes, where required, that automatically inter-trip pre-selected generating units to rapidly disconnect or de-load HVDC interconnectors following monitored transmission events that would otherwise cause unacceptable thermal overloads if the actions are not taken.
- Using Active Network Management schemes that automatically regulate output of generators to manage thermal overloads,
- Using series reactors, series compensation equipment and quadrature boosters to optimise power flows.

Post Fault Actions after Unplanned Faults

We use offline power flow analysis tools and real time network analysis tools to assess the security of the system, identify constraint boundary transfers and to determine viable post fault actions. We input constraint boundary transfers into our system operator real time tool for monitoring real-time operation. Post fault implementation strategies are prepared for all identified and monitored unplanned faults on the system for use by real time despatch engineers.

Most overhead line transmission faults are transient in nature, caused by lightning strikes or flashover onto trees and other objects in adverse weather conditions or flying objects infringing safety clearances. Overhead transmission lines are often equipped with a special protection scheme known as Delayed Auto Reclose (DAR) which, following a protection operated trip of an overhead line circuit, will reclose the tripped circuit after a 20-30 second delay during which time the fault arc has often discharged and so the circuit is returned to service automatically. If the circuit trips on reclose, indicating a permanent fault has occurred such as a fallen conductor, then the transmission circuit remains tripped and out of service. For thermal constraint boundaries, post fault actions would typically be enacted after DAR operation has occurred and the transmission circuit has failed to return to service.

Operational Tripping Schemes

We utilise Operational Tripping Schemes, where they are installed, that inter-trip specific generating units, ranging from wind farms, conventional generators and HVDC interconnectors. These can often be configured to pre-set contingencies such that for a given event potential thermal overloads within a thermal constraint boundary can be avoided by tripping or reducing output of a generator feeding the potential overload. Furthermore, this configuration can often be selected to operate after a time delay, thus allowing the tripped circuit the opportunity to return to service via DAR which can avoid unnecessary curtailing of generating units and incurring associated scheme activation costs. Where Operational Tripping Schemes control HVDC interconnectors, then the automatic scheme action can be set to change the HVDC power output to a specific level instead or trip the link as necessary.

Managing Embedded Generation Volatility

Due to the move to more decarbonised and decentralised generation sources, managing some thermal constraints on windy or sunny days in certain parts of the network has added additional challenges. This embedded generation is most likely not to be participating in the Balancing Mechanism and therefore we don’t have the real-time information on their output or the ability to buy actions to control their output. Instead we use weather information, historic demand and generation curves and more recently artificial intelligence to predict what this embedded generation is likely to do.

Sometimes in certain parts of the transmission network export from embedded generation causes a thermal export constraint that we cannot control through the Balancing Mechanism. Therefore, to manage these conditions and comply with SQSS, we enact constraint management contracts where possible.

Once we have exhausted all of our options in the Balancing Mechanism or through contract management services there are occasions where we still need to take further action to maintain a secure system. In this case the ESO would issue a System Warning often in the form of a localised Negative Reserve Active Power Margin (NRAPM). The localised NRAPM allows Emergency Instructions to be issued to the respective users to turn off the generating units behind the affected constraint boundary to avoid unacceptable thermal overloads. The System Warning will contain the period for which the warning is applicable, and the amount of actions required to achieve the volume shortfall in MW. This procedure is in line with Grid Code OC2.4.3. extract shown below;

> OC2.4.3.1 In each calendar year, by the end of week 39 The Company will, taking into account the Final Generation Outage Programme and forecast of Output Usable supplied by each Generator and by each Interconnector Owner, issue a notice in writing to:- (a) all Generators with Large Power Stations and to all Interconnector Owners listing any period in which there is likely to be an unsatisfactory System NRAPM; and (b) all Generators with Large Power Stations and to all Interconnector Owners which may, in The Company’s reasonable opinion be affected, listing any period in which there is likely to be an unsatisfactory Localised NRAPM, together with the identity of the relevant System Constraint Group or Groups.

The converse is also true i.e. when there is lack of generation within the group excessive power will flow into a group potentially causing a thermal import constraint. Such scenarios happen when the renewable generation within the group isn’t generating (low conventional or renewable sources of energy). To support demand within the group, we can either instruct generation which is connected to the transmission system out of merit order cost and if that option is not available then we can request DNO(s) to transfer some demand out of affected group(s) to a different group(s) (most of the time it will be pre-agreed).

Across the ESO and through our Forward Plan we are working with the DNOs to find methods and commercial solutions to manage these situations rather than having to rely on system warnings and emergency instructions.

Thermal Constraint Management using Market Participants

As System Operator our role is to make sure we have the right network available and configured effectively so that we can immediately respond by calling on services from our energy partners connected to our network in the event of unplanned outages occurring. We change power output in the balancing mechanism or through constrain management services accordingly to ensure that all transmission assets will operate within their rated thermal capability during and post event. Network optimisation alone will not fix all constraints and as discussed above we do rely on providers to change their output so that we can redirect flows. We do this through direct action in the Balancing Mechanism or through Constraint Management Services which we enact in varying time scales as required.

There are three ways providers can offer us Constraint Management Services. These are set out in Figure 3 below.

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Real time transmission engineers continually monitor real time thermal constraints and transfer flows across boundaries and respond to system generated alarms and the results generated by the online power flow analysis tools. This allows our control engineers to reassess and re-optimise thermal constraint limits in real time based on the real-time system configuration, actual generation and demand. We use the Balancing Mechanism (BM) for buying flexibility from providers in real time. Balancing Mechanism Units (BMUs) provide us with the information we need to make decisions around adjusting their output to manage thermal constraints, including:

- Current level of output (Physical Notification),
- Availability to import or export power to the transmission system (import and export limits),
- The price they will pay to reduce their output (a Bid) and technical information such as, ramp rates, and the level of minimum stable output.

In real time, we use this information to manage thermal constraints by adjusting the output of BMUs within a thermal constraint, whilst another BMU, outside of the thermal constraint, will be adjusted in the opposite direction. This repositioning is needed to maintain a balanced system. In the case of multiple BMUs being able to help with the constraint, we will accept the Bids or Offers that deliver the most benefit to relieve the constraint. All market participants can identify when the ESO has taken these actions as they are System Operator (SO) flagged for the purposes of Elexon settlement and identified on the BM Reports website.

We also use constraint management contracts which we enact in real time to manage specific issues which are usually of a specific localised nature. We can also trade with providers in week ahead or day ahead trading time scales to manage specific thermal constraint issues. The power system operates in a very dynamic nature, so real time decisions are based on continuous monitoring, review and optimisation of the GB power system. Our role is to ensure that the decisions we make in real time are accurate, efficient and unlock value for our customers and the end consumers.

In control room time scales, we continue to refine the system outage plans to provide system access to enable connection of new users to the transmission system, and to allow access for overhaul, breakdown repairs and maintenance of transmission assets. To provide secure delivery of electricity the outage plan is refined right up until the time the outage happens and the system is continuously monitored throughout the outage to ensure it continues to run securely.

Operability Challenges

Historically, the large synchronous power stations were not only transmission connected but also had very predictable and near constant non-variable power outputs powered by gas, coal and nuclear fuel sources which all participated in the Balancing Mechanism. The majority of power stations were in the North, close to fuel sources and largest demand centres have always been in the South of England and Wales. The UK electricity market is increasingly changing, the generation mix has significantly changed and as Electricity System Operator we are now experiencing significant levels of embedded generation to meet the overall national demand. However, most of the embedded generation is not visible to us. The ESO sees the effect of the embedded sources of energy through reducing the demand we need to supply from the Transmission system. We are experiencing fast paced changes on the transmission system due to the emergence of embedded generation, closure of large transmission connected synchronous generation as they reach end of their commercial life. In real timescales, during periods of high solar output and wind power output, we experience huge changes in power transfers and constraints between the North and South of the country. It has become challenging to confidently forecast transmission demand levels at Grid Supply Points due to the presents of embedded unmetered wind and solar generation connected to the distribution network. This generation does not provide metering to the ESO and does not participate in the BM. The variable nature of this generation which depend on local weather conditions presents a continual challenge with regards to maintaining and improving the accuracy of our offline tools and the modelling of accurate demand apportionment considering the significant penetration of embedded sources of generation. This is where the Energy Network Association, ENA, Open Networks project trials will inform and facilitate industry agreement on the Transmission Operator, TSO and Distribution System Operator, DSO interface. Please see below examples of some of the thermal constraint operability challenges faced in real-time. Also, see diagrams below showing the growth of solar embedded generation and wind generation on the Great Britain transmission system.

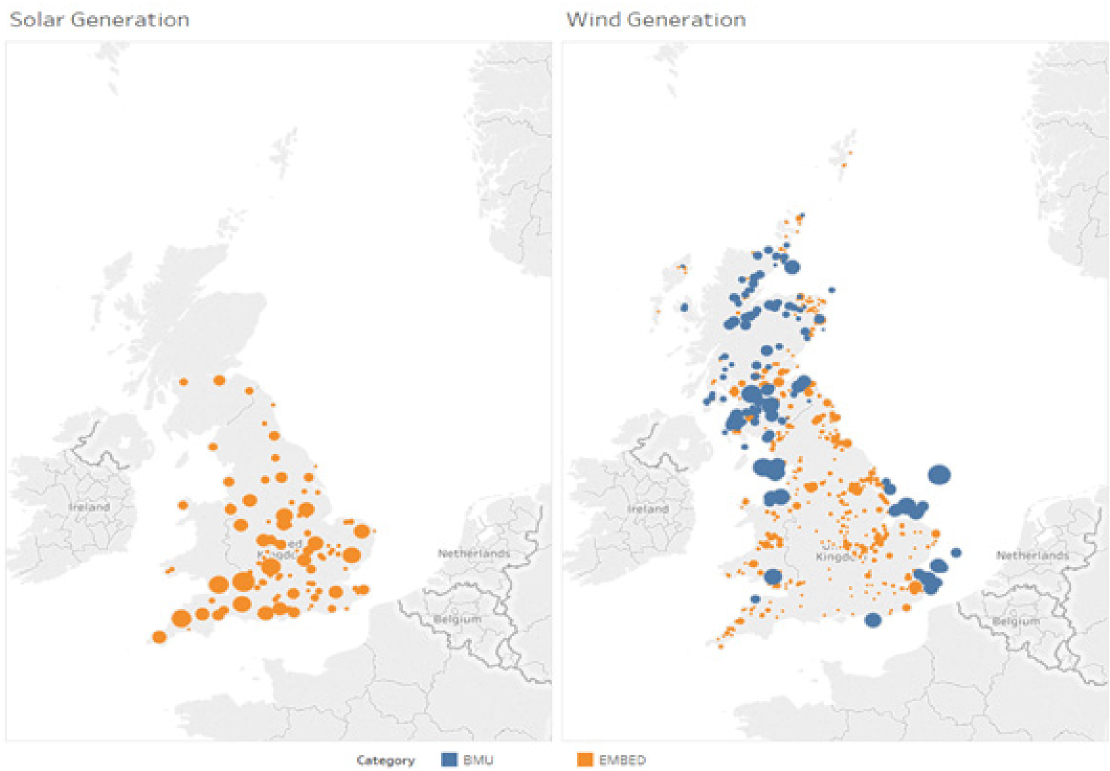
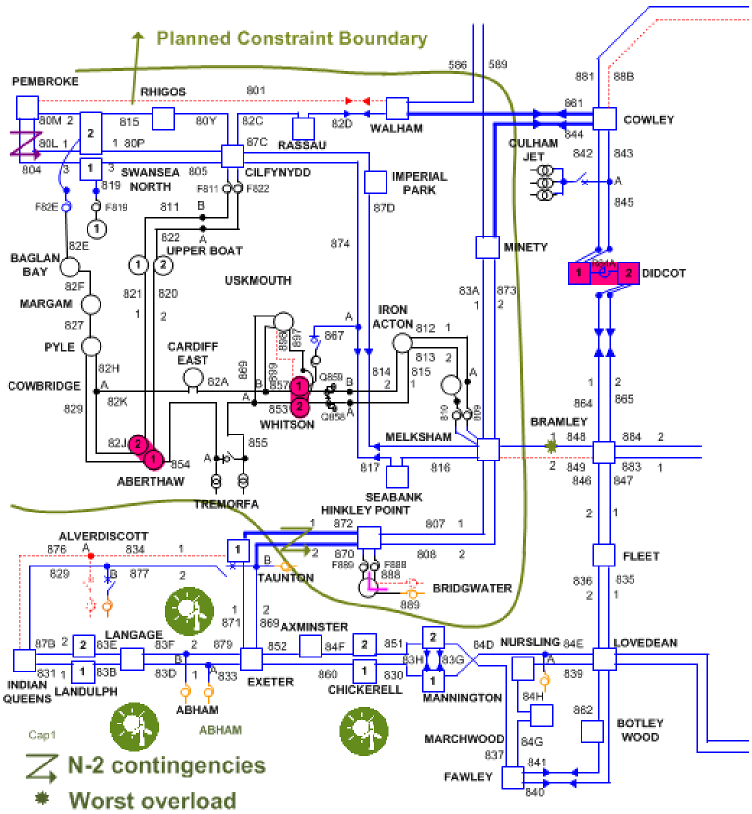


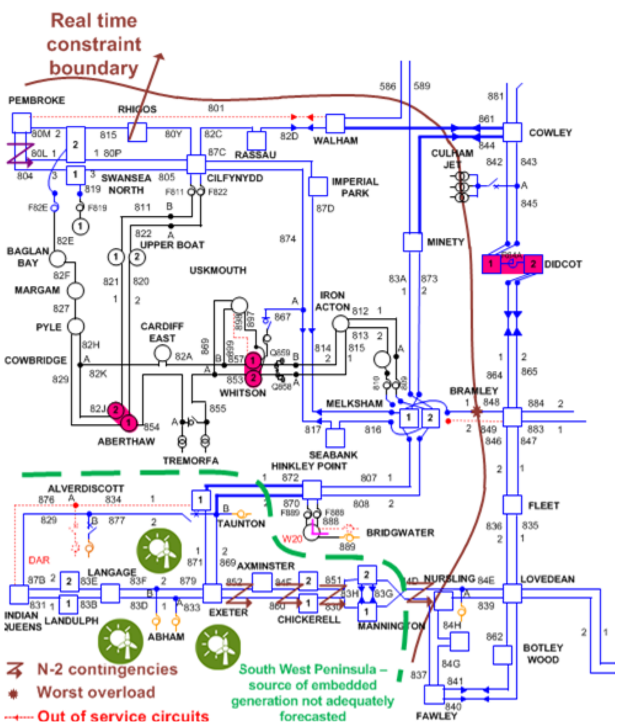
Figure 2: Embedded Generation Heat Map

Case I: Extreme weather causing potential system insecurity as forecast demand data did not account for the unknown levels of embedded generation

On Monday 6th August 2018, both the Bramley – Melksham Number 2 400kV and Pembroke – Walham 400kV circuits were out of service for planned maintenance work. The usual sequence of offline power flow studies had identified a South West Export thermal constraint which would require management of loadings on the remaining circuits for the N-2 contingency event (double circuit West of Hinkley Point tripping). The South West Export thermal constraint group covers the South Wales transmission system, this is illustrated in the figure below:



From 14:00hrs onwards, when the solar generation was highest during this clear, sunny day, the ENCC online analysis tools began reporting an unexpectedly high and unmanageable thermal overload on the Bramley – Melksham Number 1 400kV circuit for other N-2 contingencies than those previously identified namely double circuit transmission faults in the South West Peninsula. This overload was not identified in the offline assessment undertaken by the planning teams or the intra-day ENCC teams which had identified the original N-2 contingency. Real time assessment was carried out and subsequently identified a new thermal export constraint and Energy Bids were duly taken within this constraint to manage the post-fault overload for the contingency reporting. The new constraint boundary is shown below.

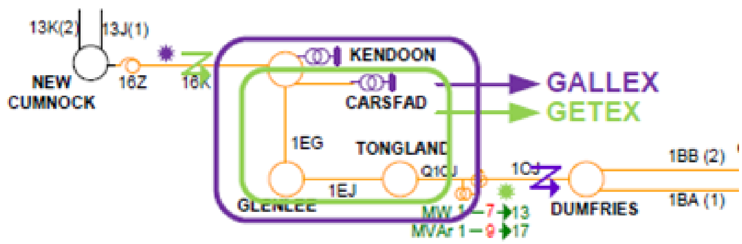


It is believed that the overload was caused by high levels of embedded solar generation in the South West Peninsula region – this was hypothesised based on unexpectedly low demand levels seen, with some GSPs even exporting power, coupled with the forecasted sunny weather. As already explained, we do not have visibility of embedded solar generation and our forecasting tools underestimated the volume of embedded generation levels ahead of real time. These reasons contributed to our offline tools not seeing the potential overloads. Missing this potential overload meant that had we suffered the N-2 contingency event we would have ran the system beyond acceptable thermal ratings until real-time actions were taken to contain the overload.

Historically, the risk of overloads such as this being missed by our offline studies have been low as our forecasts of demand and generation outputs were more accurate with lower levels of embedded generation. Post event analysis shows that when a constraint limit is changed in near to real-time, the operational costs are potentially far greater than when the constraint had been managed in planning or scheduling timescales.

Case II: Limitation of load management schemes to control identified areas of network congestion

In South West Scotland, generation mostly comes from non-BM (balancing mechanism) embedded providers. As the Dumfries and Galloway area has previously been identified as one with transmission constraints a requirement for a load management scheme was identified. These LMS automatically control output from embedded providers thus resolving transmission constraints. There are now several such schemes installed and operational within the area and these can automatically trip generation whenever a monitored line loading reaches full capacity. As the volume of embedded providers has increased in the area, the LMS isn't always enough to resolve the constraints, particularly under outage conditions. Some additional non-BM providers are now traded on a bilateral basis to avoid overloading of the transmission lines. When LMS and trades jointly are insufficient to resolve the constraint, a localised NRAPM (negative reserve active power margin) notice is issued to the market. Following this market notification emergency instructions may be issued to providers as a last resort to manage the thermal constraint and emergency instructions can then be issued to further providers



The ESO is running a regional development programme (RDP) for South West Scotland to identify and develop solutions for both distribution and transmission connected providers. The RDP will enable providers to participate in constraint management services and maximise utilisation of the network.

Potential Impacts of Future Changes on Thermal Constraint

As the generation becomes more variable due to changes in the weather, the transmission flows on the system change causing significant variations to system constraints. The above examples demonstrate some of the challenges we need to address to enable us to operate within thermal constraints. These are all 'localised' examples within a defined constraint area. We are now starting to see larger scale examples where thermal constraints have a wider ranging effect and to demonstrate is recent experience of high north to south transmission flows on the east of England with concurrent south to north transmission flows on the west during bright sunny days, coinciding with high interconnector imports from continental Europe. Altogether, these changes have led to a change in thermal constraints we experience on the network and a change in the requirements we need to manage thermal constraints in real time.

Historically, our ability to instruct the output of a large number of transmission connected conventional generators met almost all our thermal constraint management needs, this is no longer the case and we need to find new approaches to manage. To continue to deliver reliably and efficiently meeting thermal constraints in the future, we will need to develop robust visualisation tools, artificial intelligence, machine learning and a system of technologies and products to manage the challenge of increased variability of generation. Increased volumes of distributed generation on parts of the network are causing operational challenges that lead to additional costs of operating the network including constraint payments to generators operating on a part of the network that cannot accommodate their output. These changes are set to continue. This change means that more and more the ESO is having to plan on a whole system basis with the DNOs in a much more detailed way than ever before.

The existing Week 24 data exchange process is in place to ensure that system modelling information of DNO networks is up to date to allow us and TOs to model the whole network accurately. In future, our approach must provide enhanced data visibility and accuracy to retain operational resilience and situational awareness for the system operator. This will assist with accurate demand and generation data modelling required for accurate system security assessment and identification of transmission constraints. We believe greater value can be released through enhancing our ways of working with both TOs as well as DNOs and other connected parties. Any cost avoidance, reduction, or savings we make managing system constraints will directly benefit the consumer.

We aim to use our experience gained in real time operation of the GB system under the present changing environment to help address the operability challenges we face managing thermal constraints going forward. Our focus on future operability will enable us to identify new tools and implement solutions in time to resolve operability challenges before they become a threat to system security and economic system operation.

We communicate our future operability challenges to industry via our Operability Strategy Reports where we discuss the Regional Development Plans we are putting in place to tackle future operability challenges and how we are opening the Balancing Mechanism via our Wider Access initiatives aimed at breaking barriers to entry for new service providers. We cooperate with ENA to facilitate industry agreement on the future whole system operability agenda.

We aim to ensure that the ENCC remains resilient, flexible and agile with a robust ability to continue to meet the evolving operational challenges as the electricity industry continues to transform. We will focus on our transformation in the approach to real time operation and constraint management and ensure that we evolve to deliver our aim to operate a 100% zero-carbon electricity system for GB by 2025.

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