Sensitivity Factors Report

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1. Executive Summary

The TRANSITION[1] project is an Ofgem NIC funded 5-year project from 2018-2023, led by SSE-Networks, that aims at further developing DSO experience and capability with deploying local flexibility markets. Part of the objective of the work is to design several new commercial processes for flexibility markets, but also the suite of technical tools and systems required to support and deliver them. Two of the TRANSITION technical tools in particular focus for this specific report are called the Select and Dispatch (S&D) tool, and the Power System Analysis (PSA) tool.

The PSA tool (built around the core engine of the DIgSILENT PowerFactory product) has the task of evaluating where any constraints exist on the network, and the S&D tool has the role of contracting for flexibility responses from customers to mitigate them. Because the location of the flexible assets may be far from the point of the constraint, and because electricity networks may have complex topology conditions, then these two tools need a way to communicate the relative impact of flexibility action from a given market actor to relieving congestion at a distant point of constraint in the network.

That paired impact of a given flex asset dispatch action on a specific network constraint element is encapsulated in a metric called the "**Sensitivity Factor**" (SF), and this report summarises the TRANSITION work to both define this metric, and also to design a robust numerical procedure to calculate it in a practical setting of a real DNO network. Equation (1) provides a mathematical description of this metric.

$$\text{Sensitivity Factor (SF)} = \frac{\delta(\text{flow})}{\delta(\text{flex})} \qquad (1)$$

In the design of a suitable SF methodology, the TRANSITION project aimed to carry out a wide range of empirical numerical network load flow studies, furthermore on a range of network cases (from simple stylised to real world examples), so as to ensure the method arrived at was both informed and robust. A number of key questions were relevant in this context:

- What units of power flow should be used for the numerator and denominator in the SF formula above? (e.g., MVA, Amps, MW etc)
- Are the issues relevant for definition of SFs dependent on whether the constraints and flex sources are connected at EHV, HV or LV level of the distribution network hierarchy?
- What sign conventions do we need to consider in the methodology for SFs? Noting that DNO networks can be constrained in either import or export directions, and/or flex market participants can have a range of (generation, storage or demand response) technologies that can both increase, or decrease their active power impact on the network
- How is the design of the SFs methodology influenced by reactive power and voltage issues in the network, as much as active power?
- How can we define the methodology for SFs to be simple and comprehensible to a wider range of non-technical stakeholders in the flexibility market and industry more broadly?

This report summarises the design for the Sensitivity Factors that we used in the rest of the TRANSITION programme technical trials and tools. It also expands in detail on the design attributes

[1] SSEN TRANSITION (ssen-transition.com)

considered, the reasons for selection specific solutions to them, and also links to a wide range of numerical studies that support that reasoning.

The core PSA tool in use in the TRANSITION project work was the DIgSILENT PowerFactory tool, and therefore, while the high-level design principles of this report are transferable to any tool, some of the lower-level numerical procedures may need to be checked for adaptability to other commercial PSA tools.

The key conclusions and learnings of this work were:

- SFs were defined as the change in loading (MVA) on one network element with respect to the change in (MW) active power injection from one flexibility asset, as described in Equation (1). Each network element present in the model has a unique SF value with respect to a specific location of a flex asset.

- MVA or apparent power is preferable to be used as the SF formula numerator for thermal constraints since transformers keep constant power output between different voltage levels zones, and thus the $\Delta Flow$ variations in MVA across the network become straightforward. Conversely, the potential utilisation of current kA as the metric would require current flow conversions between different voltage levels defined by the transformer's turns ratios, or it would require per-unit calculations. This would be unwieldy from a numerical perspective and difficult for stakeholders to understand easily – MVA was preferable to kA therefore.

- SF values are not constant across all potential analysis timeframes, or all network topologies, or all dispatch setpoints of the flexible assets. For different network topologies, a different SF should be used. For changes in flex market actor operating point within the same network topology, or at different times of the day or week under the same base network topology, then careful analysis of the SF results should be used to guide how often they need to be updated. The TRANSITION technical trials indicated that in the real-world network examples we considered, the SFs for each asset were almost constant across a range of operating conditions for the same network topology, but often experienced step changes with changes in the topology (e.g., due to outages).

- As no significant differences were found during the SF numerical empirical studies at EHV, HV and LV parts of the network and in thew TRANSITON trials, then the same SF design process was applied no matter the network level. However, careful consideration should be applied when looking at the impact of very small kW-level LV connected flexibility assets on network flows measured in MVA much higher in the network at EHV level for example (e.g., making sure that sufficient decimal places are used in the SF calculations etc before rounding).

- It is critical that a sign convention is used in the deployment of any SF process in a flexibility market. This applies to both the directional nature of the constraint on the network (e.g., import vs export constraints on the network element), but also the nature and relative impact of the flexibility asset (e.g., is it increasing or decreasing its generation/demand level). The lower-level details of the SF sign convention applied in this report are related specifically to the PowerFactory modelling tool data structure.

- SF should account for the transmission and transformer losses within the network.

2. List of Contents

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List of Abbreviations

Bk	Block
BAU	Business As Usual
BSP	Bulk Supply Point
FA	Flexibility Asset
GSP	Grid Supply Point
HV	High Voltage
LV	Low Voltage
NE	Network Element
PF	PowerFactory
PSA	Power System Analysis
SF	Sensitivity Factor
SLD	Single Line Diagram
SEPM	Sustain Export Peak Management
SPM	Sustain Peak Management

3. Introduction

TRANSITION Project Background[2]:

The Ofgem NIC-funded TRANSITION project is a 5 year project from 2018-2023, that aims at further developing DSO experience and capability with deploying local flexibility markets, enabling non-DSO services such as peer-peer capacity trading, as well as enlightening ESO and DSO whole system coordination efforts. The TRANSITION project trials were led by SSEN and undertaken in the Oxfordshire region of SSEN SEPD DNO license area, in conjunction with the Local Energy Oxfordshire (LEO) industrial project, with ENWL, CGI and Origami as further TRANSITION project partners.

"*Flexibility*" in context of DSO network constraint management refers to a change in the generation or consumption patterns of a connected customer, in response to a commercial price signal, so that a constraint or overload on the electricity network can be maintained within safe limits.

The TRANSITION project has defined several new commercial and technical processes in support of the deployment of a DSO market for flexibility. A number of new tools have also been designed and implemented and tested through 4 periods of joint trials with Project LEO in the Oxfordshire area.

The ambition of the trials and tools were in part, to test a flexibility market workflow that used a high degree of automation (i.e., tools integrated through APIs), and either procured and/or dispatched flexibility much closer to real-time than traditionally may have been the case (e.g., using week-ahead and day-ahead market activity, as opposed to procurement years ahead of real-time, for example).

[2] SSEN TRANSITION (ssen-transition.com)

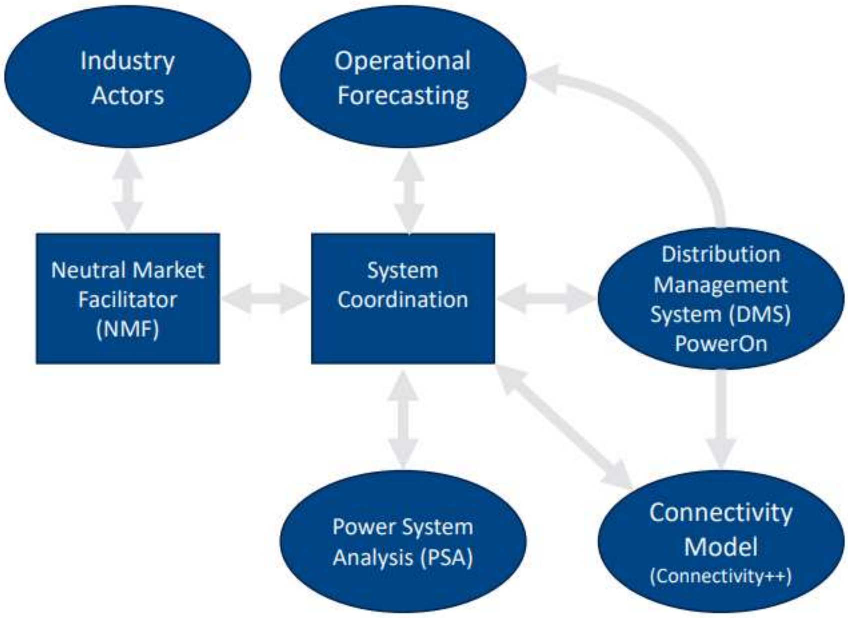

Figure 1: TRANSITION tools and process architecture

The diagram shown in Figure 1 summarises in a simple high-level manner some of the systems and tools that have been either developed or interfaced as part of the TRANSITION trial programme. These tools are listed as follows:

• **Operational Forecasting**: provides a view of demand/generation profiles at granular nodal level for 0-10 days ahead of real-time

• **Distribution Management System** (PowerOn): Provides control room view of live/real-time network connectivity and power flows

• **Power System Analysis** (PSA): Computes anticipated power flows under different near-term topology change and forecast scenarios. In this workflow, the tool in use was DIgSILENT PowerFactory.

• **System Coordinator** (WSC): Provides the core intelligence for flex market decision making, allows an input interface for control room, and manages automated data flows between sub-component DSO systems and produces the **Section/Dispatch** results for contracting and dispatch for flex.

• **Neutral Market Facilitator** (NMF): Provides a user interface portal for DSO interaction with the Industry Actors to enter/accept their available flex service volumes/costs, and for them to request approval for peer-to-peer (P2P) capacity trades

• **Connectivity model** (Connectivity++): The master model that holds the network and how customers relate to it and master repository for key network parameters (e.g.,, impedance, ratings and normal running arrangement).

Role of Sensitivity Factors in the Process Workflow

The main role of the Sensitivity Factors methodology derived in this report relates to the interaction between the System Coordinator function (which procures and dispatches flexible assets to manage the constraints) and the PSA function (which calculates the load flows on the network and thus determines where the constraints are).

In order to determine what are the least cost flexibility market actions to manage the constraint on the network, the flex Section/Dispatch task needs to know what the relative sensitivity is, or contribution, of additional generation or demand from a specific market actor, to the flows in the network at the point of the constraint. It then uses this information, along with e.g., price details such as availability and utilisation costs, to come up with an optimal set of contracts or dispatches to manage that constraint.

Therefore, the principle of a Sensitivity Factor referred to in this report, (and the methodology designed to capture it), encapsulates that very specific function.

Further Introduction of Sensitivity Factor Technical Detail

A sensitivity factor (SF) can thus be defined as the change in loading observed on the network elements such as **ST0, PT0 or BT0** shown in Figure 2, with respect to a change in power injection that can be positive or negative from the flexibility asset (FA). The FA in Figure 2 is defined as **DER_F**, and is connected downstream from the network element **ST0** for a particular point in time and for a specific network running arrangement.

Hence the SF captures the impact of a change in demand or generation at a given node with respect to the power flow somewhere else in the network, and it is defined in high level terms in Equation (1) for all network elements and all relevant flexibility market participant nodes.

$$\text{Sensitivity Factor (SF)} = \frac{\delta(\text{flow})}{\delta(\text{flex})} \qquad (1)$$

It is worth mentioning that certain simplifications are assumed with the use of Equation (1) since it considers that SF are linear and additive, which is not strictly true as the full power flow analysis is a non-linear set of equations. However, as the TRANSITION project is mainly focused on active power (MW) flexibility services and trades, then it is also likely to focus on these related sensitivity factors primarily. Thus, δ(flex) is related to MW active power flexibility only, and using reactive power i.e., MVAr in (1) is out of scope of the work in this work for now (i.e., reactive power flexibility services are not included in the market trials or the technical modelling).

Moreover, SF are unlikely to be precisely constant across all timeframes of analysis or all network topologies. SF can change by topology switching or contingency analysis scenario. Additionally, depending on network operating point and the true non-linearity of the full power flow calculation (e.g., at different network loading conditions such as periods of maximum or minimum customer demand), SF can also change. Thus, a ‘version control’ or ‘metadata’ process would need to be applied to the SF values that are relevant for any given analysis or timeframe or network topology condition.

The application of SF within the network can be diverse regarding resolution of network constraints. For example, one FA can resolve single or multiple network constraints. Also, multiple FA can be used for resolving either a single or multiple constraints. The process derived in this report is generalisable to all cases in this respect. An example is depicted in Figure 2.

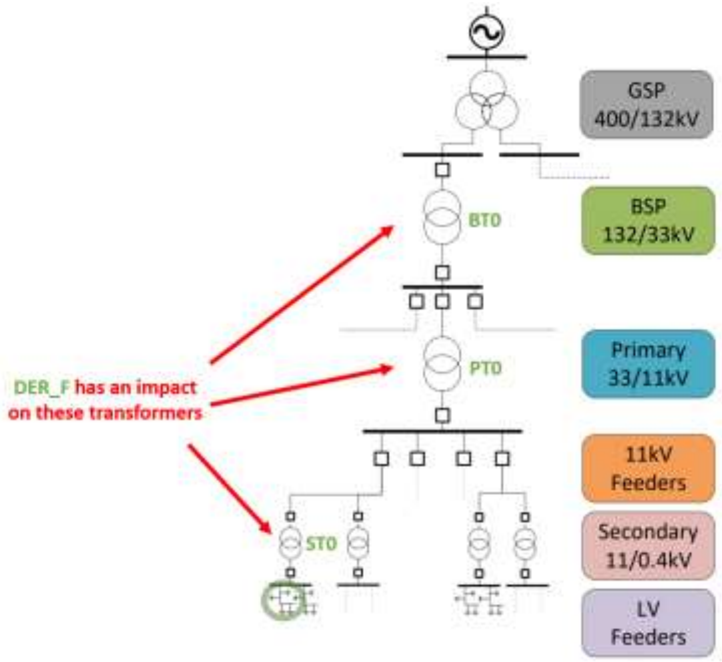

Figure 2: Sensitivity factors illustrative example for one FA (DER_F) resolving a single constraint in ST0, PT0 or BT0

4. Sensitivity Factors Design Criteria and Assumptions

The consolidated design of the SF process presented in Section 5 and illustrated in Figure 7 and Figure 8 resulted from the numerical results of a wide range of empirical studies, that aimed to capture the FA performance for solving network constraints in different network conditions and varying FA operating set points. Through the course of conducting those empirical studies, a number of key questions were deemed to be influential in the design of the SF methodology, and in this section, we present a simple list of those, as well as some key conclusions to them that are supported by the numerical results presented in later Sections.

It is important also to note that while the general principles of the Sensitivity Factors (SF) methodology described in these Sections are transferable to any PSA tool, the lower level numerical detail of this approach is based on the DIgSILENT PowerFactory (PF) data structure for modelling network elements (e.g., lines and transformers) and for calculating different electrical parameters (e.g., current, active power, apparent power, etc.). For any other PSA tool in use, then careful investigation may need to be carried out at the outset to determine if any small changes are required.

1. *Should the sensitivity factors' numerator/denominator for the network constraint flows and dispatch amounts be best defined using active power (MW), apparent power (MVA) or current (A)[3]?*

SF MVA or Amps: To determine the $\Delta Flow$ units to be used in a network element (NE) illustrated in the SF equation in Bk-24 (Figure 6), two different options were assessed. Particularly, the $\Delta Flow$ in any network element could be calculated in either MVA or Amperes.

[3] From now on, the terms active power, apparent power, and current are referred to as MW, MVA, and A, based on the units used, respectively.

Figure 3 depicts a comparison performed in two sets of parallel transformers from Witney and Yarnton BSP network models (further details in Case A from Section 9.1.2). As the results show, the SF calculations utilizing MVA or kA performed more or less exactly the same. SF calculations could be determined by capturing the change in the power flow in any of these two electrical variables.

However, since transformers keep constant power output between different voltage levels zones within the network, the $\Delta Flow$ calculations in MVA can be determined directly. Conversely, the utilisation of kA becomes more complex since current flow conversion must be conducted between different voltage levels defined by the transformer's turns ratios. Alternatively, per-unit calculations must be employed.

Thus, for simplicity and to avoid these complexities associated with current, it is assumed that network element $\Delta Flow$ is always captured as a function of MVA variations regardless of the network voltage levels.

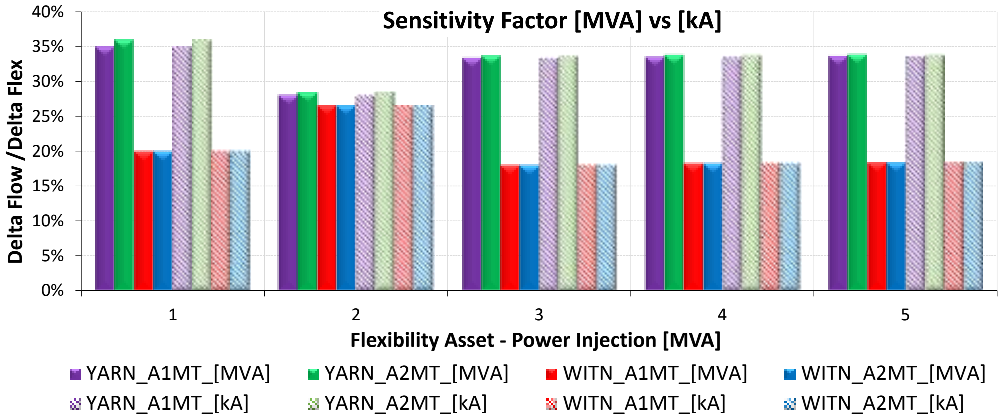

Figure 3: SF calculations comparison between MVA and Amps

2. What issues may be different at EHV, HV, and LV for the SF calculation?

No significant differences are found in the results of the empirical studies when FA is located at the EHV, HV or LV part of the network. Examples in Section 9.1.1 refer to LV implementation of FA, whereas Section 9.1.2 involves FA at HV. The methodology proposed here is exactly the same. However, it is worth mentioning that FAs located far away from the Feeder head may have a distinct impact to resolve network constraints occurring in lines or transformers upstream of the FA (i.e., at the HV side) due to e.g., losses.

One item to also consider may be if the size of the FA is very small (e.g., Smax=0.055 MVA) and care may need to be taken to ensure that any numerical issues are addressed in terms of e.g., number of decimal places used in the calculations if very small kW size assets are relieving constraints much higher up the network typically measured in MVA.

3. *How might we define sign conventions for import/export constraints, and furthermore for the relative contribution of increased or decreased generation or demand response to them?*

It is critical that the SF methodology derived, which will later be used to underpin a flexibility market process, is able to distinguish between issues caused by import or export constraints in a certain part of the network, and distinguish between the impact of increased generation or demand from the candidate flexibility assets being evaluated for contract or dispatch selection. The different cases are illustrated in Figure 4.

Figure 4. Illustration comparing services with different direction SPM (import) and SEPM (export)

As pointed out, the low-level implementation detail of the SF methodology presented in this report is specifically related to the PowerFactory modelling structure. Within this context, the negative active power flow direction is always defined as the flow coming from the upstream to the downstream part of the network, and it is characterised as an Import flow as shown in Figure 5 (figure section extracted from Figure 7), Bk-7-10-11 as the case of the lines. This means all lines and cables in the model should be modelled with their "from" terminal/busbar being the one with the shortest electrical distance to the GSP and their "to" terminal/busbar being the one with the longest electrical distance to the GSP.”. The positive power flow direction is described as the power flow going from the network downstream to upstream, and it is classified as an Export flow as illustrated in Bk-7-8-9. This sign convention aligns with the PF format for allocating negative or positive active power flows in lines and transformers. An example of a reverse power flow is described in Section 9.1.2.1 Case A.

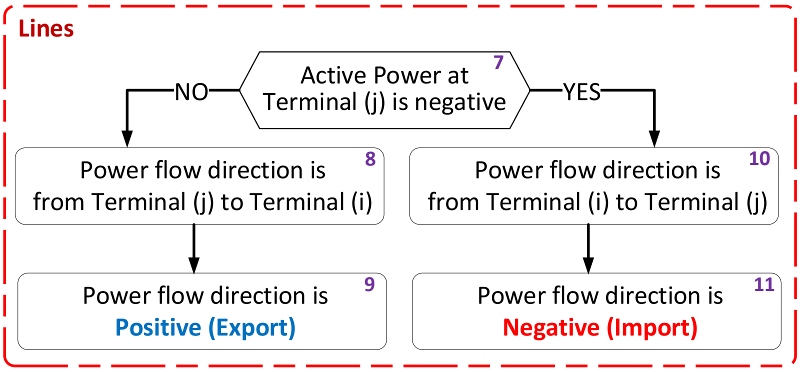

Figure 5: Definition of negative and positive power flow for lines modelled in PowerFactory

4. How does the SF methodology relate to voltage/reactive power issues in this network?

In all the study cases included in the present report, we primarily evaluated the impact of increased or decreased active power MW output from the flex assets, and hence the assets had no direct impact on reactive power flow in the model. However, on a distribution network, changes in active power will still slightly impact the voltage profile and thus wider reactive power flows in that region of the network. These issues were accounted for in the fact that we used MVA rather than MW as the metric of choice.

In addition to the above questions, different sets of assumptions are made during the deployment of the SF methodology. Some are related to the PF format for modelling network elements, whereas others are created to determine the value of the SF application during network constraint occurrences. Their details are listed below.

- Lines Models: It is assumed that all lines are modelled from the upstream to the downstream part of the network, and thus they follow the PowerFactory format for modelling lines. Consequently, Terminal (i) is always the nearest busbar to the GSP, whereas Terminal (j) is the furthest. This assumption is employed in Bk-2 in the SF process detailed in Figure 7**Error! Reference source not found.**.

- Transformers Models: In the PowerFactory structure for modelling transformers, the HV-Side is always the closest busbar from the GSP. Conversely, the LV-Side is the remotest busbar. This assumption is applied in Bk-4 in the SF process detailed in Figure 7.

- Losses: To account for the transmission losses that occurred in lines and step-down transformers, all the electrical parameters described in Bk-3 and Bk-5 from Figure 6 are captured at the downstream terminal of lines (Terminal (j)) and transformers (LV-Side).

5. What consideration needs to be taken of simplicity in the SF design and how it can be easily communicated to stakeholders or persons of a non-technical audience?

The success of a flexibility market implementation for a DSO relies on active participation from a wide range of stakeholders, and it also relates to several processes of a commercial rather than technical nature. Therefore, it is critical that the SF metric can be easily understood by such an audience.

For this reason, the key SF metric was decided as the delta(flow in MVA)/delta(flex asset output in MW) in this workflow, as opposed to using e.g., current flow in kA, as this would be less understandable by a non-technical audience.

Though the deeper details of the methodology in the later sections is quite technically complex and embedded in some of the detail of PowerFactory tool, the end result is a simple linear metric that has tangible understanding for wider stakeholders.

5. Sensitivity Factors Methodology – Detailed Description

The process describing the methodology deployed to determine the SF for the TRANSITION project is depicted in Figure 7 and Figure 8. The process involves two key stages. Mainly, Stage 1 includes the Network Initial State Analysis, which aims to capture the current conditions of the network elements such as active power, apparent power, loading and power flow direction before calculating the SF. Stage 2 is defined as Network Flexibility Assets Analysis. It is mainly used to carry out the SF calculations of the network elements (i.e., lines and transformers) with respect to the flexibility assets within the network.

It is worth mentioning that the deployed process illustrated in Figure 7 and Figure 8 for conducting the SF calculations is based on the PowerFactory structure and definition of busbars, lines, transformers, active and apparent power flow and direction, among others. Thus, the methodology will need to be adapted if a different power systems tool such as PSSE, ERACS or ETAP is used. The SF process description is as follows.

5.1 Stage 1: Network Initial State Analysis

Stage 1 is characterized by several steps represented in Figure 7 through 19 blocks. Each block aims to perform and capture different calculations to determine the initial state of the network by solving a basic load flow calculation before a flexibility asset starts to provide or consume active power within the network.

Block-1 (Bk-1) in Figure 7 shows the active power injection or consumption equation in MW (further details in Stage 2) defined as P_{Flex_k} for the flexibility asset (FA), with $k = 1, 2, 3 \dots total\ number\ of\ FA$.

Where $P_{Flex_k\_Max}$ represents the maximum power output from the FA, and n_{Step} is the number of power output steps in which the FA injects or consumes power from the grid. As the aim of Stage 1 is capturing the initial states of the network without any contribution from FA, $n_{Step} = 0$. It is worth mentioning that the use of n_{Step} is meant to make the SF number more resistant to slight changes in load flow results that are not linear. It involves calculating the difference in load flow results over a few steps of changes in active power dispatch from the FA. By doing this, we can account for any effects of non-linearity during the SF calculations.

The next step is to find the busbars of the closest lines to the grid supply point (GSP) and identify the high and low voltage terminals from the transformers.

Bk-2 illustrates how the line's busbars are defined and identified in PowerFactory. So Terminal (i) is described as the upstream busbar in the network, whereas Terminal (j) is the downstream part of the network (i.e., further from the GSP). Then, as shown in Bk-3 the apparent power, active power and loading are obtained in each line at Terminal (j) to account for the lines transmission losses that occurred within the network.

Transformers follow a similar process to the lines. Bk-4 defines the high voltage (HV) and low voltage (LV) sides of the transformers. These are represented as HV-Side and LV-Side in PowerFactory. Next, in Bk-5 to include the transformer losses, the apparent power, active power and loading are determined at the LV-Side of each transformer.

Bk-6 is then used for defining the power flow direction of each of the network elements under analysis (i.e., lines and transformers) at $n_{Step} = 0$.

For the case of the lines, Bk-7 is utilised to obtain the active power sign at Terminal (j). So, following the PowerFactory PSA tool definition for power flow direction, the active power sign is considered negative if the power flow goes from Terminal (i) to Terminal (j) as depicted in Bk-10. Conversely, power flow is defined as positive if it goes from Terminal (j) to Terminal (i) (Bk-8). Next, positive power flows are classified as an Export condition (Bk-9), meaning the active power in a line is from the downstream to the upstream part of the network. On the contrary, Negative power flows as characterised as an Import (Bk-11) condition.

Bk-12 describes the active power sign at the LV-Side of the transformers. The negative sign refers to the power flow from the HV-Side to the LV-Side (Bk-15) of the transformer, whereas the positive sign is defined from LV-Side to HV-Side (Bk-13). Positive active power flows are then classified as an Export condition (Bk-14), and negative as an Import condition (Bk-16). Next, the power flow directions of both lines and transformers are stored in Bk-17.

After defining the active power flow magnitudes and directions of lines and transformers, the next step is to search for potential occurrences of constraints within the network (Bk-18). The constraints in lines and transformers are defined as the current flow in kA above their rated current values (i.e., exceedances). It is worth mentioning that in this case, the exceedances in lines and transformers can occur at either terminal/side of the network element.

The last step of Stage 1 is defining the flexibility requirements in MW (Bk-19) to remove partially or entirely the constraints within the network. To this end, the lines and transformers' exceedances in kA are converted to MW using the equation (1)(i.e., "how much active power change in this element do we need to bring it back within allowed tolerances?"), and then used as the input values for FA requirements.

$$P = \sqrt{3} * V * I * \cos\theta \qquad (1)$$

Where, V is the actual voltage at the terminal in kV, I the exceedances in kA and cos θ the power factor.

5.2 Stage 2: Network Flexibility Assets Analysis

Stage 2, is also characterized by several tasks as shown in Figure 8. The main objective is to describe the steps performed to conduct the flexibility assets analysis and computations of the SF concerning each FA.

The first task is defined in Bk-20, and like Bk-1 from Stage 1, shows the active power injection or consumption equation from the FA in MW. In this case, the power injection refers to FA mainly generators capable of generating and injecting active power into the network, and thus $P_{Flex_k} = (+)$. On the other hand, when the storage system during charging conditions or demand response assets are consuming active power from the grid, the FA contribution to the grid is considered to be $P_{Flex_k} = (-)$.

Then, the active power, apparent power and loading for lines and transformers at Terminal (j) and LV-Side respectively, are calculated for each n_{Step} defined for each FA. (Bk-21 and Bk-22). Next, a key step before calculating the SF need to be performed. The step involves determining the power flow direction of the MVA on each of the assets of interest (network elements such as lines and transformers) with respect to the FA (i.e., $S_{NE\_n_{Step}}[MVA]$). Due to the way apparent power is calculated, this quantity lacks any sign or direction. Instead, this is artificially created based on the NE active power flow at each n_{Step} characterised by $P_{NE\_n_{Step}}[MW]$ as illustrated in Bk-23.

The SF equation for any NE is shown in Bk-24 (Figure 6). It represents the change in loading in MVA defined as $\Delta Flow\ [MVA]$ observed on the selected NE with respect to the change in power injection or absorption in MW from the FA described as $\Delta Flow_k\ [MW]$. Then, $\Delta Flow\ [MVA]$ is calculated as the change in flow in the NE at n_{Step} and n_{Step_0} (i.e., $P_{Flex_k} = 0$) described as $S_{NE_{n_{Step}}}$ and $S_{NE_{n_{Step0}}}$ respectively. The change in the active power flow of the FA at n_{Step} and n_{Step_0} (i.e., $P_{Flex_k} = 0$) is defined as $P_{Flex_{k_{n_{Step}}}}$ and $P_{Flex_{k_{n_{Step0}}}}$ respectively. It is essential to mention, as depicted in Bk-24 that $\Delta Flow\ [MVA]$ and $\Delta Flow_k\ [MW]$ are always considered to be a positive value.

Sensitivity Factors (SF) Calculations 24

$$\text{Network Element(NE)} = \frac{\Delta Flow\ [MVA]}{\Delta Flex_k[MW]} = \frac{|(S_{NE_{n_{Step}}}) - (S_{NE_{n_{Step_0}}})|[MVA]}{|(P_{Flex_{k_{n_{Step}}}}) - (P_{Flex_{k_{n_{Step_0}}}})|\ [MW]}, \qquad n_{Step} = 1, 2, 3, \dots 100$$

Figure 6: Block-24 from the sensitivity factor process flow chart part 2

The SF power flow direction is determined by the NE active power flow change, as illustrated in Bk-25. It is defined by $\Delta Flow_{NE}\ [MW]$, and it is the difference between $P_{NE\_n_{Step}}$ and $P_{NE\_n_{Step0}}$. Next, the power flow direction (i.e., sign) of $\Delta Flow_{NE}\ [MW]$ is compared with $P_{NE\_n_{Step0}}$ (i.e., $P_{Flex_k} = 0$) as shown in Bk-26. If they have identical signs e.g., (+), it means that the SF power flow direction is in the same direction as n_{Step_0} (Bk-28). Conversely, if the sign is different, the SF power flow direction is opposite to n_{Step_0} (Bk-27). Then, the SF sign of the NE under analysis with respect to FA (i.e., P_{Flex_k}) is stored in Bk-29. An example of SF power flow direction is described in Section 9.1.2.1 Case A.

One of the final tasks of Stage 2 is the SF validation process performed in Bk-30. The aim is to apply the SF values obtained in previous steps to confirm whether the actual loading in MVA from NE at n_{Step} matches the change in flow caused by the active power injection or consumption from the FA, characterised by the SF magnitude and direction computed in Bk-24 and Bk-25, respectively.

Thus, the SF value of the NE at n_{Step} described as $SF_{NE\_n_{Step}}[MVA]/[MW]$ is multiplied by the power output from the FA in MW at n_{Step} defined as $P_{Flex_{k}\_n_{Step}}[MW]$. This value is always considered positive (i.e., absolute product between the two). After, the initial MVA of the NE at n_{Step0} (i.e., $S_{NE\_n_{Step0}}[MVA]$) is either added or subtracted to this product depending on SF direction (i.e., sign) determined in Bk-27 and Bk-28. The result is also considered as an absolute value (Bk-30), and it should be precisely the amount of MVA flowing along the NE at n_{Step} characterised by $S_{NE\_n_{Step}}[MVA]$. If this condition is met, then the calculation of the SF is correct. Otherwise, an error between the Bk-23 and Bk-29 is produced; thus these steps need re-evaluation.

The SF final calculation step is performed in Bk-31 and mainly it provides the SF as an array if different n_{Step} have been considered during the calculations. On the contrary, a unique SF value is offered when a single n_{Step} is utilised. The SF computations are an iterative process (Bk-32) that finishes when all the desired FA have been employed and, therefore, the SF analysis has been completed (Bk-33).

Figure 7: Sensitivity Factors process flow chart part 1

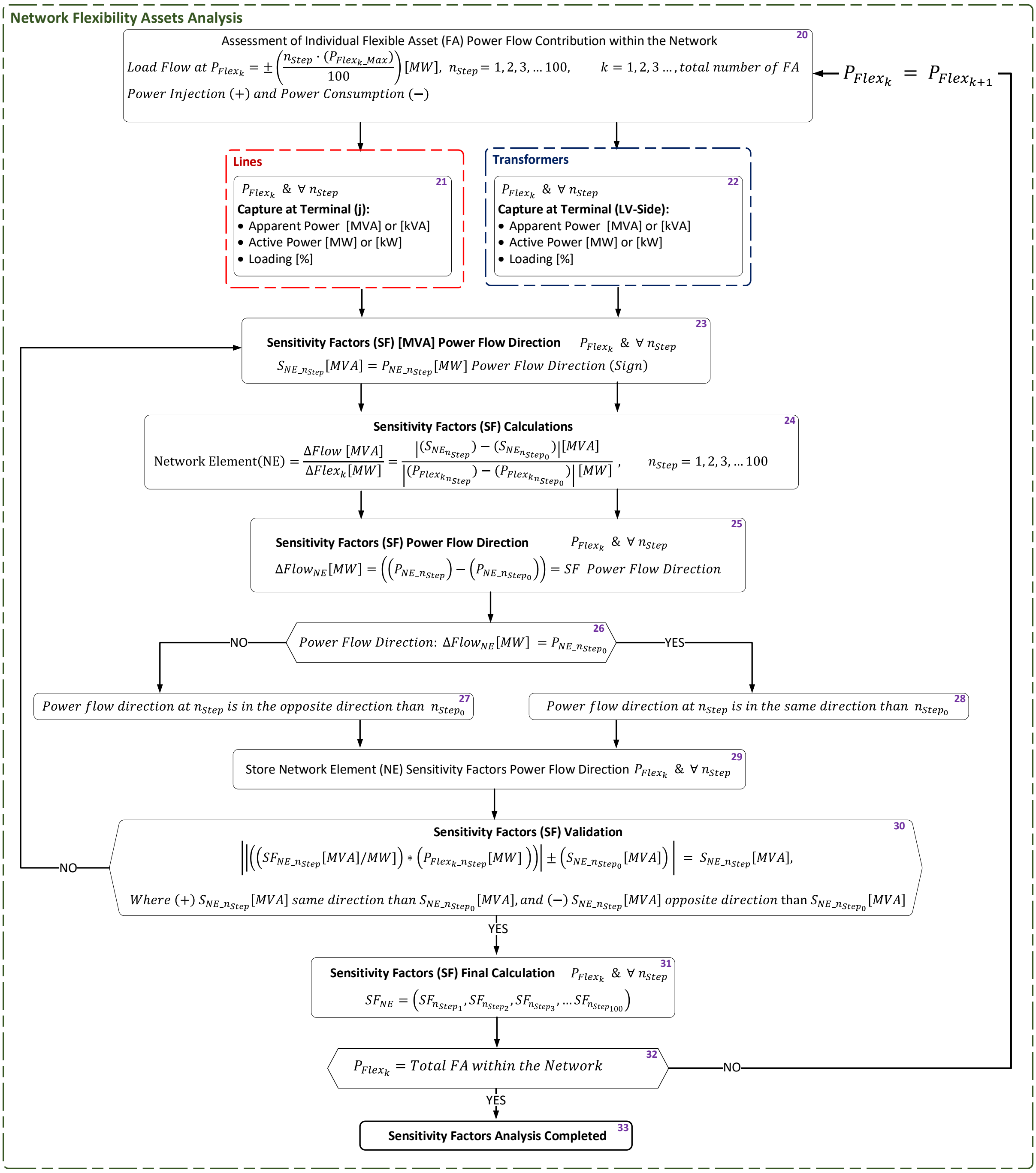

Figure 8: Sensitivity Factors process flow chart part 2

5.3 Numerical Example

A numerical example of the application of the SF methodology is shown in Figure 9. The example is based on the Witney and Yarnton BSP network model. A 10 MW generator is located at the Primary Substation Chipping Norton, acting as FA. The aim is to investigate the effect of the FA on the NE loading (i.e., lne_11731_13330_1) when injecting different levels of MW, and to validate the SF methodology discussed in the previous section. Figure 9 displays the location of the FA and the NE under study.

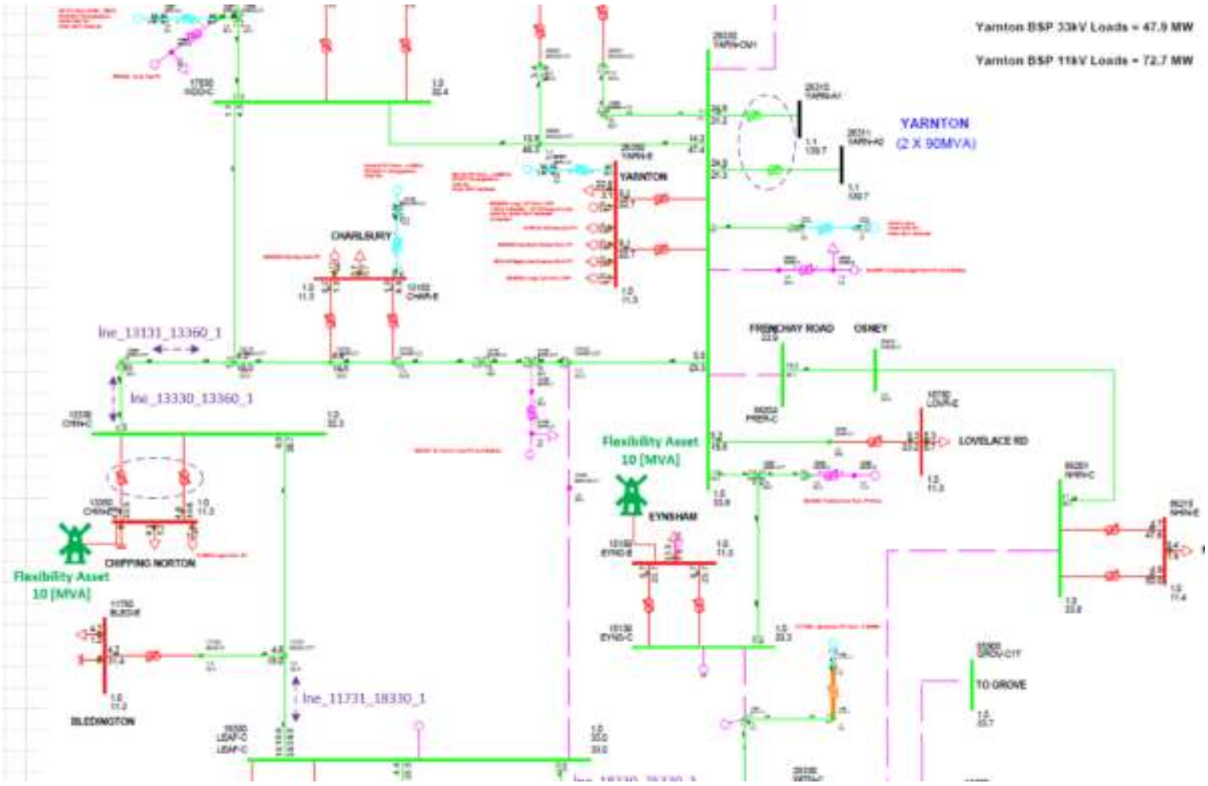

Figure 9: Extract of Witney and Yarnton SLD illustrating the location of the FA at the Primary Substation Chipping Norton and NE under focus

Figure 10 shows the results of the main calculations performed for the SF computation. The last column includes the location of each operation with regard to the SF methodology (i.e., Figure 7 and Figure 8).

Figure 10 in row 1, illustrates the FA steps characterised as n_{Step}, which is defined in 10 steps of 10% each with respect to the previous n_{Step}. The FA power output $P_{Flex_k}[MW]$ is detailed in row 2. Then, the line "lne_11731_13330_1" (row 3) is selected for determining the effect of $P_{Flex_k}[MW]$ at different n_{Step}, so the apparent power of the line at each step is included in row 3.

$P_{Flex_k}[MW]$ at $n_{Step} = 0$, and $S_{NE\_n_{Step_0}}$, $P_{NE\_n_{Step_0}}$ are highlighted in grey in Figure 10. These are considered the initial state of the line "lne_11731_13330_1" and the FA. Next, rows 3, 6 and 7 provide the data regarding MVA ($S_{NE\_n_{Step}}$), MW ($P_{NE\_n_{Step}}$) and level of loading of the selected line for each n_{Step} described in row 1.

Row 4 shows the $P_{NE\_n_{Step}}[MW]$ sign extracted from row 6, which is used for allocating the $S_{NE\_n_{Step}}[MVA]$ power flow direction (row 5) as detailed in Bk-23. In this case the negative active power flows shown in red happen from $n_{Step} = 0$ to $n_{Step} = 90$. This means the power flow direction is from line Terminal (i) to Terminal (j) as detailed in Bk-7-10-11. The positive active power flow occurs at $n_{Step} = 100$ (Figure 5 in blue), and refers to the current flow going from Terminal (j) to Terminal (i) as described in Bk-7-8-9.

Once the $S_{NE\_n_{Step}}$ sing allocation is completed, the $\Delta Flow\ [MVA]$ defined by $\left(S_{NE_{n_{Step}}} - S_{NE_{n_{Step0}}}\right)$ absolute values are performed in row 8. Later, the $\Delta Flow_k[MW]$ described by $\left(P_{Flex_{k_{n_{Step}}}} - P_{Flex_{k_{n_{Step0}}}}\right)$ is calculated directly since $P_{Flex_{k_{n_{Step0}}}} = 0$ and then $P_{Flex_{k_{n_{Step}}}}$ is immediately extracted from row 2.

The next step is to determine $\Delta Flow\ _{NE}[MW]$ described by $\left(P_{NE_{n_{Step}}} - P_{NE_{n_{Step0}}}\right)$ in Bk-25. The results are shown in row 9, and they are used to identify the SF power flow directions, which are evaluated in row 10.

Row 11 entails the SF computations of line "lne_11731_13330_1" with respect to Chipping Norton FA at every n_{Step}. After that, the final step is the SF validation process details in Bk-30. This is a crucial step since it aims to prove the accuracy of the SF estimations for each n_{Step}. The results are displayed in row 12 and must be identical to the ones depicted in row 3 to confirm the SF computations have been performed correctly.

Row	Active Power												SF Process
1	Flexibility Asset Steps (%)	0	10	20	30	40	50	60	70	80	90	100	Bk-20
2	Network Element (NE)	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	
	Flexibility Asset (Chipping Norton)	0	1	2	3	4	5	6	7	8	9	10	
	Apparent Power												
3	Network Element (NE)	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	Bk-21
	lne_11731_13330_1	9.18	8.17	7.16	6.16	5.16	4.18	3.21	2.26	1.40	0.90	1.28	
4	[MW] Power Flow Sign	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	Bk-23
5	[MVA] Sign = [MW] Sign	-9.18	-8.17	-7.16	-6.16	-5.16	-4.18	-3.21	-2.26	-1.40	-0.90	1.28	
	Active Power												
6	Network Element (NE)	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	Bk-21
	lne_11731_13330_1	-9.17	-8.15	-7.13	-6.12	-5.11	-4.10	-3.09	-2.09	-1.08	-0.08	0.92	
	Line Loading												
7	Network Element (NE)	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	Bk-21
	lne_11731_13330_1	135	119	104	89	74	59	45	32	20	13	18	
	Delta Flow (MVA)												
8	Network Element (NE)	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	MVA	Bk-24
	lne_11731_13330_1		1.01	2.02	3.02	4.02	5.00	5.97	6.92	7.78	8.28	10.46	
	SF - Delta Flow (MW) Power Flow Direction												
9	Network Element (NE)	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	Bk-25
	lne_11731_13330_1		1.02	2.04	3.05	4.06	5.07	6.08	7.08	8.08	9.09	10.08	
10	SF Power Flow Direction		Opposite	Opposite	Opposite	Opposite	Opposite	Opposite	Opposite	Opposite	Opposite	Opposite	Bk-26-27-28
	SF Calculations (Delta Flow/Delta Flex)												
11	Network Element (NE)		MVA/MW	MVA/MW	MVA/MW	MVA/MW	MVA/MW	MVA/MW	MVA/MW	MVA/MW	MVA/MW	MVA/MW	Bk-24
	lne_11731_13330_1		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	
12	SF Validation	1.00	8.17	7.16	6.16	5.16	4.18	3.21	2.26	1.40	0.90	1.28	Bk-30

Figure 10: SF numerical example

6. Sensitivity Factors Implementation – Empirical Case Studies

The SF methodology described and tested in Section 5 is applied to assess its suitability (i.e., SF magnitude and direction) to actual flexibility assets within the network. To this end, the Cowley Local BSP network model, part of the TRANSITION trials, is used. The model is depicted in Figure 11 and includes four 90 MVA BSP transformers coloured in black, which feed Cowley Local busbar at 33 kV. Also, the network model contains seven Primary Substations coloured in red. However, only four are modelled in detail, meaning all their 11kV Feeders are included. Namely, Berinsfield, Wallingford, Kennington and Rose Hill Primary Substations.

To calculate the SF of a FA with respect to a line or transformer, a load flow evaluation is performed to evaluate the changes in active power flow magnitudes and directions within the model. The aim is to capture the loading profiles of the selected NE to understand the contribution of FA during network constraint occurrences. It is relevant to stress that depending on the FA size, location and type its operation could help or deteriorate the level of loading happening in NE.

The following sections investigate four different study cases for the SF implementation. The study cases are divided into two main cases. The first study case aims to assess the contribution of FA during an import constraint, whereas the second case intents to evaluate the impact of FA during export constraints. The description of the study cases is as follows.

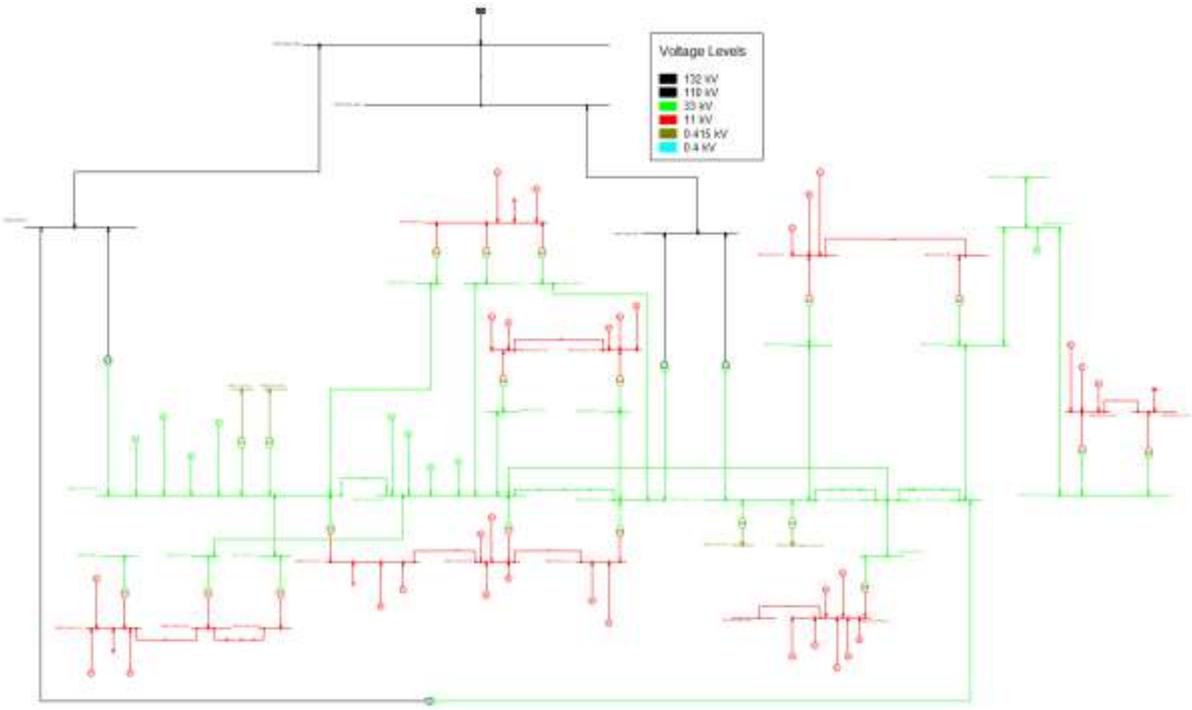

Figure 11: Cowley Local BSP Network Model used for SF implementation

6.1.1 SF Import Case

The import case refers to a network constraint originating within the network where the power flow direction comes from the upstream to the downstream side of the network. In this case, the constraint is resolved by increasing the generation or decreasing the demand downstream of the constrained NE.

During the present studies, it is assumed that the network topology remains unchanged, FAs reduce or increase active power injection, and their reactive power contribution within the network is entirely neglected, and thus the SF stays fixed during these specific operational scenarios and set points at each step. Also, normal network operating conditions are considered during the snapshot power flow application. Two Primary Substations are selected for conducting the import case studies. In particular, Kennington and Rose Hill Primary Substations, which are depicted in Figure 12 and Figure 13, respectively. The FA SANDFORDHYDRO_HYD_SP5249601797_F with Pmax=0.4 MW located downstream of the Terminal 85814 KENN-E-S1 (Figure 12) in Feeder KENN_E6L5 is used for solving the network constraint occurrences in the Kennington Primary Substation transformer KENN_C1MT. The FA ROSEHILLCC_DSR_SP5318803371_F with Pmax=0.315 MW located downstream of the Terminal 85817 ROSH-E-S1 (Figure 13) in Feeder ROSH_E2L5 is utilized for removing the network constraint occurrences in the Rose Hill Primary Substation transformer ROSH_C1MT.

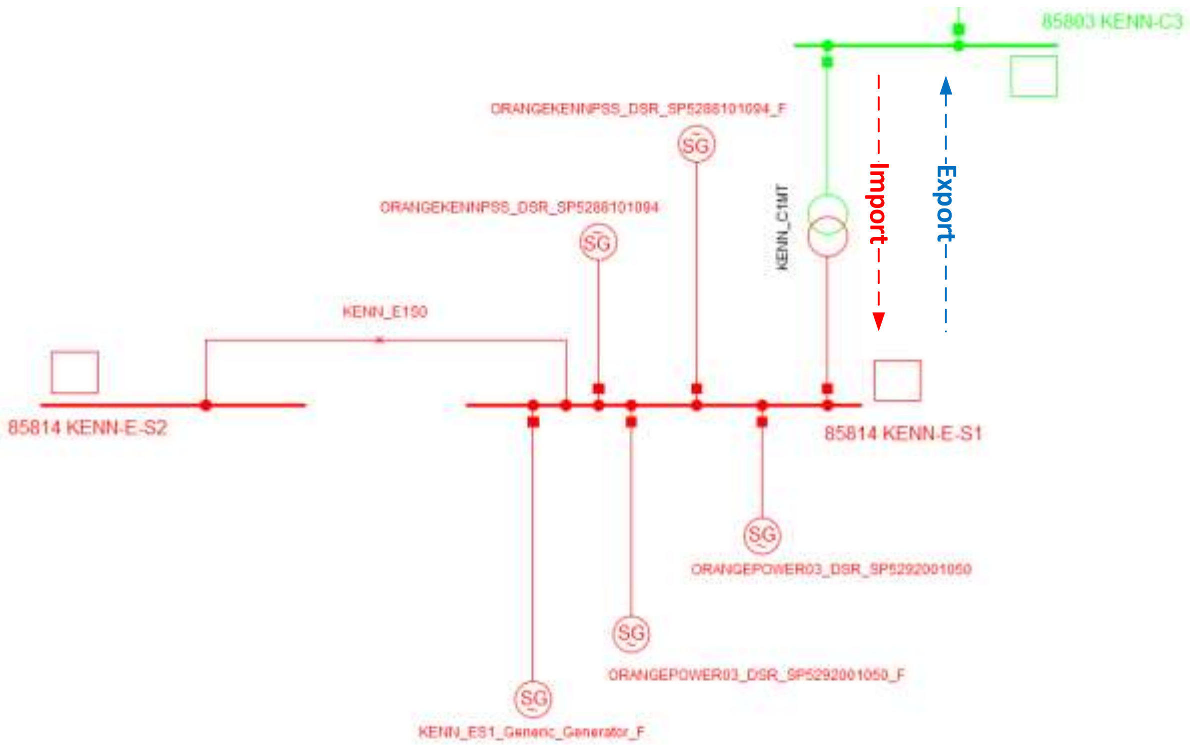

Figure 12: Modelling of Kennington Primary Substation in Cowley Local BSP network model

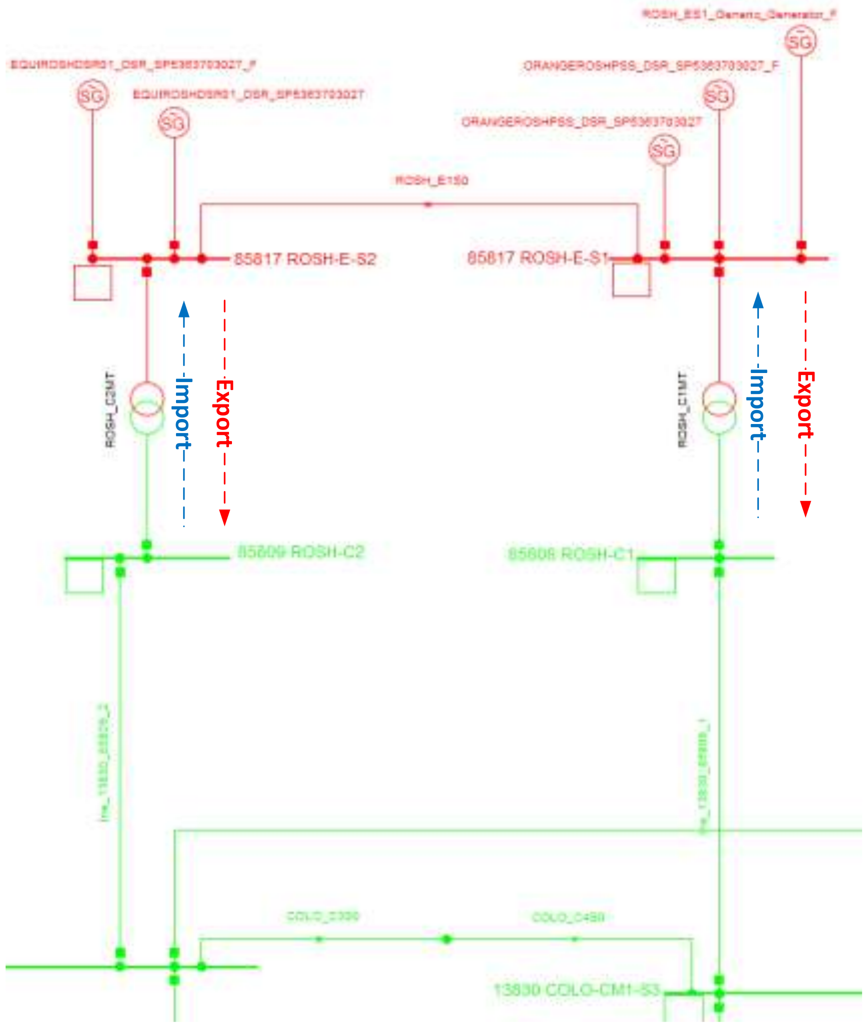

Figure 13: Modelling of Rose Hill Primary Substation in Cowley Local BSP network model

6.1.1.1 Import Case: Radial Interconnection

Figure 14 shows the loading effect in MW of transformer KENN_C1MT during an import constraint when the FA (i.e., Sandfordhydro_F) reduces the power injection. The vertical axis P_LV [MW] refers to KENN_C1MT loading, which is defined by the orange bars in Figure 14. The second vertical axis plots the active power output from the flexibility asset (*Pflex*) [MW], and it is represented by the blue line in Figure 14. The horizontal axis defines the FA power injections steps (i.e., 11) used for managing the constraint in KENN_C1MT.

A complementary set of results regarding the SF calculations are additionally included in Table 1. The actual SF values obtained from each step are defined as “SF Value”. The SF calculated sign is described as “SF Sign”, whereas the SF power flow direction is “SF Power Flow Direction”. Also, the type of network constraint (e.g., import or export) is included in Table 1. Finally, the level of exceedances in kW is added to illustrate the impact in each step of the FA power injection with respect to the transformer KENN_C1MT loading defined in MW. It is worth mentioning that the approach used for describing all the import and export cases through graphs and tables in Section 6 is identical.

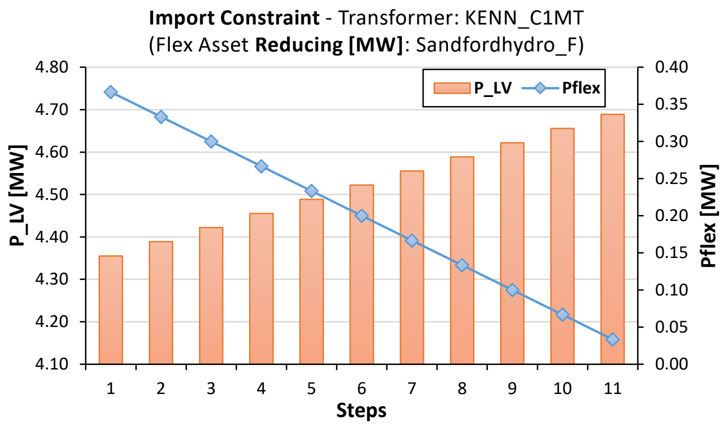

Figure 14: Import Case - Active power loading of transformer KENN_C1MT when FA reduces active power injection

Table 1: Import Case - SF calculations of KENN_C1MT when FA reduces active power injection

FA Power Injection Steps	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SF Value [MVA]/[MW]	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
SF Sign (+) or (-)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
SF Power Flow Direction (Opposite Constraint)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Type of Constraint (Import or Export)	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp
Exceedances [kW]	-0.53	-0.56	-0.59	-0.62	-0.65	-0.68	-0.71	-0.74	-0.76	-0.79	-0.82

Figure 14 clearly shows that as *Pflex* (blue line) characterised by the FA Sanfordhydro_F (synchronous machine) reduces the power injection in each step, the loading in KENN_C1MT P_LV (orange bars) increases. So the import constraint on the transformer becomes more critical (i.e., higher MW flowing through KENN_C1MT can be expected). This phenomenon can be better explained with the support of the SF variables listed in Table 1.

Table 1 in row 2 displays the SF values obtained for KENN_C1MT at each step. As expected, due to FA (Sanfordhydro_F) being directly connected downstream of the Terminal 85814 KENN-E-S1 (Figure 12), the SF of KENN_C1MT is very close to one. However, due to the reactive power flowing through KENN_C1MT, mainly required to satisfy the Kennington Substation demand, the $\Delta Flow\ [MVA]$ variations are affected in each step, so SFs reach a value of 0.9 MVA/MW only. Also, according to the calculations performed, the SF sign is negative in the case of the import constraint. As a result, the resulting power flow in KENN_C1MT induced by the FA is in the same direction as the constraint. Consequently, the FA location and performance are worsening the network condition and, in turn, the loading in KENN_C1MT. This effect is clearly reflected in Table 1 by the growth in Exceedances kW in every step.

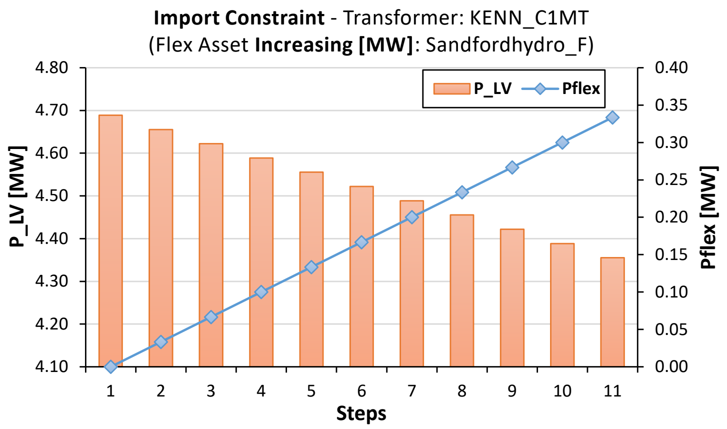

Figure 15: Import Case - Active power loading of transformer KENN_C1MT when FA increases active power injection

Table 2: Import Case - SF calculations of KENN_C1MT when FA increases active power injection

FA Power Injection Steps	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SF Value [MVA]/[MW]	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
SF Sign (+) or (-)	1	1	1	1	1	1	1	1	1	1	1
SF Power Flow Direction (Opposite Constraint)	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Type of Constraint (Import or Export)	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp
Exceedances kW	-0.82	-0.79	-0.76	-0.74	-0.71	-0.68	-0.65	-0.62	-0.59	-0.56	-0.53

Conversely, Figure 15 illustrates that as *Pflex* (blue line) increases the power injection in each step, the loading in KENN_C1MT P_LV (orange bars) decreases, and so does the import constraint on the transformer. The SF in this case, is also 0.9 MVA/MW as shown in Table 2 for each step, but the SF sign is positive. This means the resulting power flow in KENN_C1MT once the FA begins to inject active power into the system, goes in the opposite direction than the constraint. Consequently, a loading reduction in KENN_C1MT is achieved, described by the decrease in the KENN_C1MT exceedances.

Hence, Figure 14 and Figure 15 show two different applications for the same FA (Sandfordhydro_F) under identical network conditions (i.e., import constraint), but with two different outcomes regarding the KENN_C1MT loading. Also, Table 1 and Table 2 listed the SF variables of these two applications, which are also distinct. So by looking at the graphs and tables results, it could be concluded that a FA could help to resolve or worsen a network constraint. Its performance will be determined by its location with respect to the affected element, and whether it is increasing or reducing its power injection. Still, with the support of the SF variables such as MVA/MW, sign (+ or -) and power flow direction with respect to the constraint, a more informed decision could be taken by DSO. Mainly, since SF can be considered as a simple (and linear) approach to understand the network impact of specific FA during different operational conditions.

6.1.1.2 Import Case: Mesh Interconnection

Compared to the Kennington substation, a different series of results are obtained for Rose Hill Primary Substation (Figure 13). Particularly, because the Rose Hill substation is fed through two parallel transformers and thus it has a more mesh interconnection than Kennington. Also, the FA in Rose Hill substation characterised by ROSEHILLCC_DSR_F refers to a demand response asset that can shift or increase its demand when required.

Figure 16 shows the results of an import constraint that occurred in Rose Hill Primary Substation (Figure 13). Particularly, in one of the two parallel transformers feeding Terminal 85817 ROSH-E-S1, namely, transformer ROSH_C1MT. Figure 16 illustrates that as *Pflex* reduces the power injection, i.e., shift the FA demand into a different period, the loading in P_LV is diminished. This can be explained because the overall demand on Rose Hill is being decreased mainly by the FA, and thus less active power flowing through ROSH_C1MT is required.

The SF of ROSH_C1MT with respect to ROSEHILLCC_DSR_F is displayed in Table 3. Due to the interconnection nature of the Rose Hill substation (i.e., two parallel transformers) and the FA location, which is downstream Terminal 85817 ROSH-E-S1, the SF is equal to 0.5 MVA/MW for each of the parallel transformers (i.e., ROSH_C1MT and ROSH_C2MT). SF Sign is positive, so the SF power flow direction is opposite to the constraints, which has a negative sign according to the sign convention defined in Section 5. As a result, a reduction in the ROSH_C1MT Exceedances KW are achieved. Thus, in this case, the FA (ROSEHILLCC_DSR_F) in Rose Hill Primary Substation is helping to alleviate the network constraint that occurred in ROSH_C1MT.

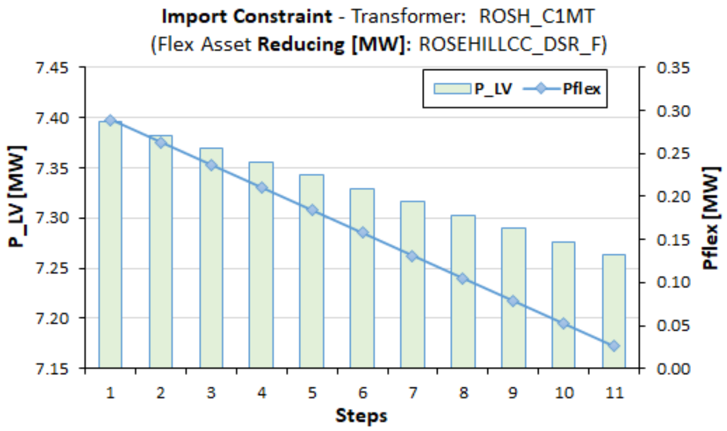

Figure 16: Import Case - Active power loading of transformer ROSH_C1MT when FA reduces active power injection

Table 3: Import Case - SF calculations of ROSH_C1MT when FA reduces active power injection

FA Power Injection Steps	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SF Value [MVA]/[MW]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SF Sign (+) or (-)	1	1	1	1	1	1	1	1	1	1	1
SF Power Flow Direction (Opposite Constraint)	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Type of Constraint (Import or Export)	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp
Exceedances kW	-2.76	-2.74	-2.73	-2.72	-2.71	-2.69	-2.68	-2.67	-2.66	-2.64	-2.63

On the contrary, when the FA increases the demand, the loading in ROSH_C1MT worsens at each step. Figure 17 shows the effect of increasing *Pflex* (i.e., FA increases demand) in P_LV. The loading on ROSH_C1MT becomes much higher as more active power is required from the downstream Terminal 85817 ROSH-E-S1.

Table 4 provides the SF calculations for the ROSH_C1MT transformer. SF remain at 0.5 MVA/MW at each step since the FA remains in the same location and the network topology is unchanged. However, in this case, SF Sign becomes negative and equal to the import constraint sign. As a result, the resulting power flow in ROSH_C1MT induced by the FA active power requirement is in the same direction as the constraint. Therefore, in this case, ROSEHILLCC_DSR_F is making the situation worse, which is clearly reflected by the ROSH_C1MT Exceedances growth.

Hence, as in the case of Kennington Primary Substation, in Rose Hill one FA could also have a different impact within the network when dealing with import constraints. The impact relies on the FA application regarding its increase or reduction in the active power injection or consumption. In this case, by looking at the results from Figure 16 and Figure 17, demand response assets such as ROSEHILLCC_DSR_F help to resolve an import constraint as long as a demand shift occurred. Otherwise, an increase in demand will cause an increase in the NE exceedances.

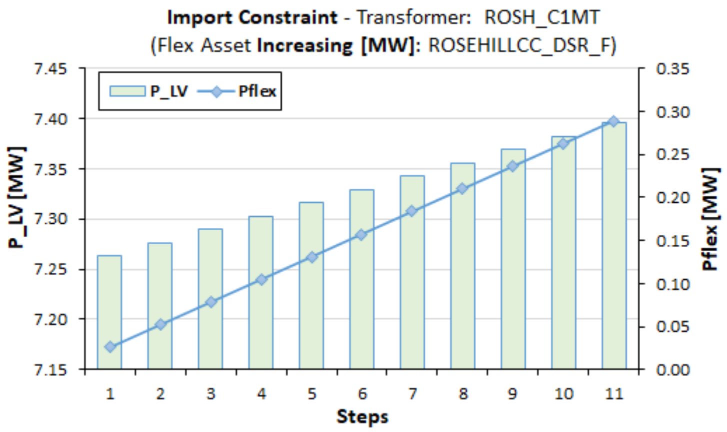

Figure 17: Import Case - Active power loading of transformer ROSH_C1MT when FA increases active power injection

Table 4: Import Case - SF calculations of ROSH_C1MT when FA increases active power injection

FA Power Injection Steps	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***
SF Value [MVA]/[MW]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SF Sign (+) or (-)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
SF Power Flow Direction (Opposite Constraint)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Type of Constraint (Import or Export)	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp	Imp
Exceedances kW	-2.63	-2.64	-2.66	-2.67	-2.68	-2.69	-2.71	-2.72	-2.73	-2.74	-2.76

6.1.2 SF Export Case

The export case refers to a network constraint originating within the network where the power flow direction is coming from the downstream to upstream the side of the network. In this case, the constraint is resolve by increasing the generation or decreasing the demand downstream of the constrained NE. .

As the import case, it is assumed that the network topology remains unchanged, that FAs reduce or increase active power injection, and their reactive power contribution within the network is entirely neglected, and thus the SF stays fixed during these specific operational scenarios and set points at each step. Also, normal network operation conditions are considered during the snapshot power flow application.

Kennington and Rose Hill Primary Substations were selected for conducting the export case studies. They are depicted in Figure 12 and Figure 13, respectively. Also, FA SANDFORDHYDRO_HYD_SP5249601797_F with Pmax=0.4 MW is used for solving the network constraint occurrences in transformer KENN_C1MT. The FA ROSEHILLCC_DSR_SP5318803371_F with Pmax=0.315 MW is utilised for removing the network constraint occurrences in ROSH_C1MT.

6.1.2.1 Export Case: Radial Interconnection

Figure 18 shows the loading effect in MW of transformer KENN_C1MT during an export constraint when the FA (i.e., Sandfordhydro_F) reduces the power injection. Figure 18 clearly shows that as *Pflex* (blue line) reduces the power injection in each step, the loading in KENN_C1MT P_LV (orange bars) is also reduced, and thus the export constraint on transformer KENN_C1MT. This can be explained by the fact that reducing the active power from Sandfordhydro_F causes a reduction in the generation surplus produced in 85814 KENN-E-S1. Consequently, a decrease in the export constraint.

This event can be better explained with the support of the SF calculations listed in Table 5. As expected, and as pointed out during the import study case the SF of KENN_C1MT with respect to Sandfordhydro_F is equal to 0.9 MVA/MW. The SF Sign is negative, different from the positive sign designed to the export constraints (sign convention defined in Section 5). This means that the active power coming from FA is opposite to the export constraint in KENN_C1MT. As a result, a decrease in the KENN_C1MT Exceedances is produced, as shown in Table 5.

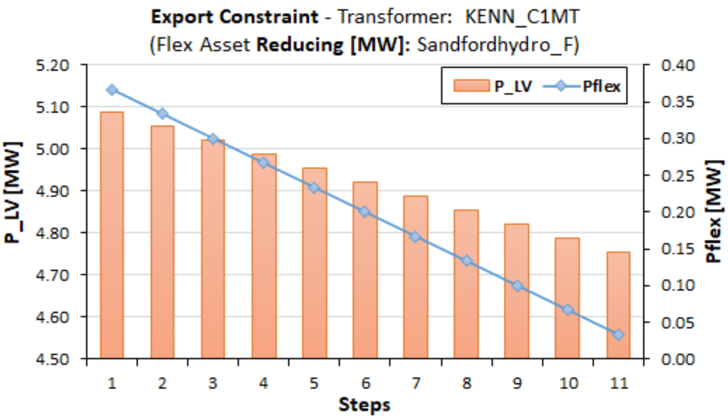

Figure 18: Export Case - Active power loading of transformer KENN_C1MT when FA reduces active power injection

Table 5: Export Case - SF calculations of KENN_C1MT when FA reduces active power injection

FA Power Injection Steps	1	2	3	4	5	6	7	8	9	10	11
SF Value [MVA]/[MW]	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
SF Sign (+) or (-)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
SF Power Flow Direction (Opposite Constraint)	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Type of Constraint (Import or Export)	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp
Exceedances kW	1.09	1.06	1.03	1.00	0.97	0.94	0.91	0.88	0.86	0.83	0.80

On the other hand, Figure 19 illustrates that as *Pflex* (blue line) increases the power injection in each step, the loading in KENN_C1MT P_LV (orange bars) also rises. So the export constraint on the transformer becomes more critical. The SF in this case, is also 0.9 MVA/MW as shown in Table 6 for each step, but the SF Sign is positive identical to the export constraint (i.e., same power flow direction). This means that Sandfordhydro_F contributes to the surplus of active power generation in Terminal 85814 KENN-E-S1. Consequently, a loading increase in KENN_C1MT is achieved, which is described by the growth in the KENN_C1MT exceedances illustrated in Table 6.

Hence, as in the case of the import constraints, a FA can help resolve or deteriorate a network condition during export constraints. This situation is clearly reflected in Figure 18 and Figure 19. However, with the support of SF parameters as those listed in Table 5 and Table 6 a better informed decision could be taken regarding applying a FA with respect to the constraint occurring within the network. Particularly, considering the SF variables such as MVA/MW, sign (+ or -) and power flow direction with respect to the constraint. The performance of the FA will be determined by its location with respect to the affected element and whether it is increasing or reducing its power injection.

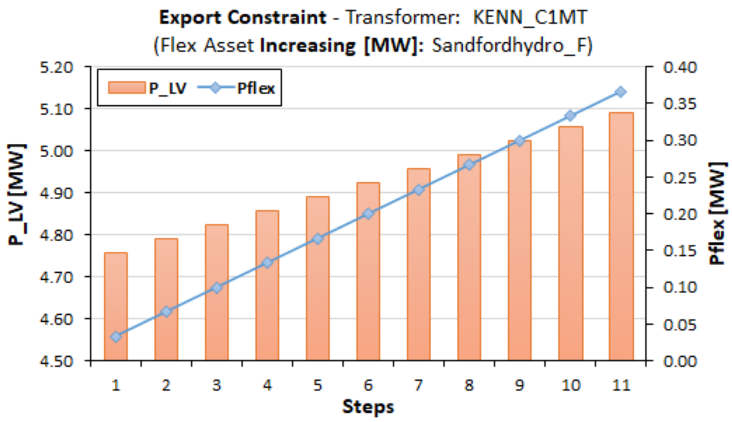

Figure 19: Export Case - Active power loading of transformer KENN_C1MT when FA increases active power injection

Table 6: Export Case - SF calculations of KENN_C1MT when FA increases active power injection

FA Power Injection Steps	1	2	3	4	5	6	7	8	9	10	11
SF Value [MVA]/[MW]	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
SF Sign (+) or (-)	1	1	1	1	1	1	1	1	1	1	1
SF Power Flow Direction (Opposite Constraint)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Type of Constraint (Import or Export)	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp
Exceedances kW	0.80	0.83	0.86	0.88	0.91	0.94	0.97	1.00	1.03	1.06	1.09

6.1.2.2 Export Case: Mesh Interconnection

Figure 20 shows the results of an export constraint that occurred in Rose Hill Primary Substation (Figure 13). Particularly, in one of the two parallel transformers feeding Terminal 85817 ROSH-E-S1, namely, transformer ROSH_C1MT. Figure 20 illustrates that as *Pflex* increases power consumption (demand increases), the loading in P_LV is reduced. This can be explained due to the overall demand on Rose Hill being raised mainly by the FA, and thus, less surplus of active power is produced in Terminal 85817 ROSH-E-S1, resulting in fewer MW flowing through ROSH_C1MT.

Table 7 displays the SF of ROSH_C1MT with respect to ROSEHILLCC_DSR_F. The SF is roughly equal to 0.42 MVA/MW for each step. This value is slightly lower than the import case, and it is mainly affected by the MVAr in Terminal 85817 ROSH-E-S1 during an export constraint. SF Sign is negative, so the SF power flow direction is opposite to the constraints, with a positive sign designed for the export cases. As a result, a reduction in the ROSH_C1MT Exceedances KW is achieved.

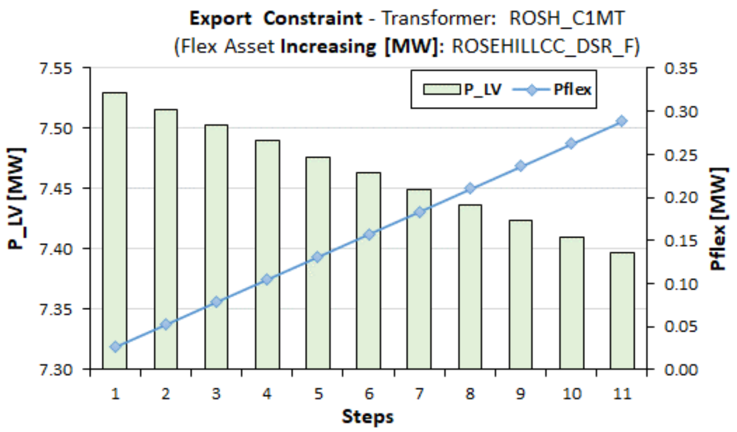

Figure 20: Export Case - Active power loading of transformer ROSH_C1MT when FA increases active power injection

Table 7: Export Case - SF calculations of ROSH_C1MT when FA increases active power injection

FA Power Injection Steps	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SF Value [MVA]/[MW]	0.43	0.43	0.43	0.43	0.43	0.42	0.42	0.42	0.42	0.42	0.41
SF Sign (+) or (-)	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
SF Power Flow Direction (Opposite Constraint)	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Type of Constraint (Import or Export)	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp
Exceedances kW	2.726	2.714	2.703	2.691	2.68	2.669	2.658	2.647	2.636	2.625	2.614

Conversely, when the FA starts to reduce the demand, the loading in ROSH_C1MT worsens at each step. Figure 21 shows the effect of lowering *Pflex* (i.e., FA shift demand) in P_LV during the export constraint. The loading on ROSH_C1MT becomes much higher as more surplus of active power is generated in Terminal 85817 ROSH-E-S1.

Table 8 provides the SF calculations for the ROSH_C1MT transformer. SF remain approximately equal to 0.42 MVA/MW at each step (FA location and network topology remain unchanged). However, SF Sign becomes positive and equal to the export constraint sign in this case. As a result, the resulting power flow in ROSH_C1MT induced by the FA active power requirement is in the same direction than the constraint. Therefore, in this case, ROSEHILLCC_DSR_F is worsening the situation, reflected by the ROSH_C1MT Exceedances growth listed in Table 8.

Hence, as in the case of the import study cases, the FA in Rose Hill could also have a different impact within the network when dealing with export constraints. The contribution of ROSEHILLCC_DSR_F to resolve the export constraint is determined by the FA performance. In this case, by looking at the results from Figure 20 and Figure 21, in addition to the SF parameters from Table 7 and Table 8, ROSEHILLCC_DSR_F helps to resolve the export constraint only during an increase in demand. Otherwise, a decrease in demand (i.e., demand shift) will cause an increase in the ROSH_C1MT exceedances, and therefore the operational network condition worst, as expected.

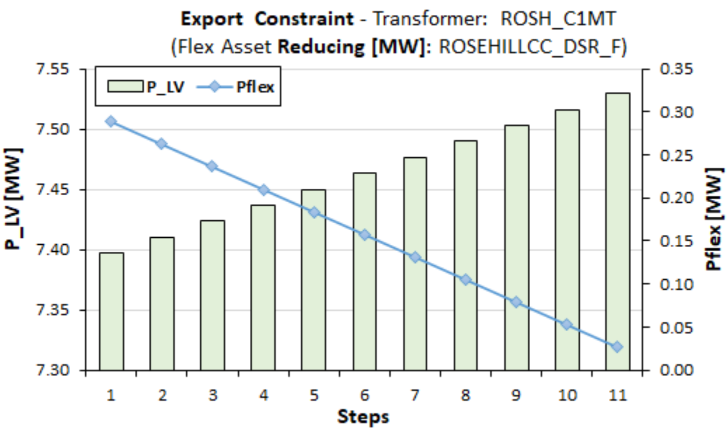

Figure 21: Export Case - Active power loading of transformer ROSH_C1MT when FA reduces active power injection

Table 8: Export Case - SF calculations of ROSH_C1MT when FA reduces active power injection

FA Power Injection Steps	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
SF Value [MVA]/[MW]	0.43	0.43	0.43	0.43	0.43	0.42	0.42	0.42	0.42	0.42	0.41
SF Sign (+) or (-)	1	1	1	1	1	1	1	1	1	1	1
SF Power Flow Direction (Opposite Constraint)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Type of Constraint (Import or Export)	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp	Exp
Exceedances kW	2.614	2.625	2.636	2.647	2.658	2.669	2.68	2.692	2.703	2.714	2.726

7. Sensitivity Factors Key Learnings

The SF calculations are performed using the designed method described in Section 5, which resulted from several numerical/experimental studies that were investigated throughout the entire process of building and validating the methodology. Some empirical power flow case studies were used to design the SF process, whereas others were utilised for testing and validating the SF performance. The key findings regarding the SF modelling and calculations across all these studies are described as follows:

- SF values are not constant across all analysis timeframes or all network topologies. SF parameters change during network reconfigurations, operating conditions (i.e., contingency scenarios) and operational set points such as different levels of consumer demand. Also, SF may change during the variations of power output from the FA. Hence, for different network topologies, a different SF most likely should be used. For changes in operating point with the same network topology (e.g., different times of the day or week under the same base network topology), then careful analysis of the SF results should be used to guide how often they should be updated for use in any flex market process. The calculation of a SF value in the context of operating a half-hourly real time flex market is of course time consuming, and therefore, judicious use of computational resource should be taken in respect to whether it makes a significant difference or not to the SF value to update it very regularly or not.

- SFs in the TRANSITION use case are defined as the change in loading (MVA) on one NE with respect to the change in MW active power injection from one FA, meaning that each network element present in the model has a unique SF value for a specific location of a FA. Many-to-many and other second-order interactions were not explored in this work.

- The lower-level details of the SF methodology described in the report heavily relates to the DIgSILENT PowerFactory data structure for modelling network elements (e.g., lines and transformers) and for calculating different power flow parameters (e.g., current, active power, apparent power, etc.) in the network. Thus, while the high-level principles of the design implemented here are transferable to any PSA tool, the lower-level set of modelling and calculation assumptions may not be directly applicable to other power systems software (such as PSSE, Sincal, ETAP, ERACS, and PSCAD, among others) without careful investigation of the power flow modelling attributes of those tools.

- MVA or apparent power in this work was concluded as the most suitable SF numerator for thermal constraints since transformers keep constant power output between different voltage levels zones, so the $\Delta Flow$ variations in MVA become straightforward. Conversely, the utilisation of kA would require current flow conversions between different voltage levels defined by the transformer's turns ratios, or would require per unit calculations.

- No significant differences were found during the SF calculations at EHV, HV and LV parts of the network. However, one point of note may be that careful consideration should be applied when looking at the impact of very small kW-level flexibility assets on network flows measured in MVA much higher in the network at EHV level for example (e.g., making sure that sufficient decimal places are used in the calculations etc before rounding).

- It is absolutely critical that a sign convention is used in the deployment of any SF process in a flexibility market. This applies to both the directional nature of the constraint on the network (e.g., is it an import or an export constraint on the network element), but also the relative directional impact of the flexibility asset (e.g., is it increasing or decreasing its generation/demand level). The sign convention applied in this report relies on the PowerFactory modelling structure and sign convention. The negative active power flow direction is always defined as the flow coming from the upstream (shortest distance to the GSP) to the downstream part of the network. In contrast, opposite power flows are described as positive.

- SF should account for the transmission and transformer losses within the network. Depending on the type of constraints defined as import or export, SF should be calculated at the opposite side of the current flow originated by the constraint from the affected element. For example, during a step-down transformer export constraint, the HV side should be considered the reference terminal for the SF computations. Reactive power values from of each NE may influence the SF performance during the $\Delta Flow\ [MVA]$ calculations. The effect has a significant impact on SF particularly during under-utilised NE (i.e., low level of loading).

8. Use of the Sensitivity Factor Methodology in the TRANSITION Technical Trials

The SF design methodology in this project was deployed and tested not just in the conceptual/desktop power flow modelling conditions in this report, but also actually used to support the close to real-time flexibility market trials in the real world, as part of the TRANSITION Technical Trial period in the Oxfordshire network. This section summarises with a small set of examples, some indicative experiences in this respect.

Figure 22 illustrates the topological layout of one part of the Oxfordshire network where some constraints were simulated during the flex market trials. The Cowley Local Bulk Supply Point (BSP) has a group of four 132/33kV transformers. The normal running arrangement is depicted in this graphic, whereby there are two 33kV busbars in this substation (the Main and the Reserve), these busbars are each connected to two of the upstream transformers, and there is a single bus coupler circuit breaker (CB), referred to as COLO_C8L5, that sits in between them that is usually kept in the open state. Below each of the two sections of the BSP (Main and Reserve) there are a number of Primary substations and flexible assets that were taking part in the market trials. It's worth noting that in the normal running arrangement, when the busbar coupler COLO_C8L5 is open, some Primary substations are supplied via Main and some via Reserve.

In these flex market trials, we considered a number of different Flexibility Service types (Sustain, Secure and Dynamic), and therefore, considered a range of possible topological issues in this part of the network that re typically associated with those service types. For example, we studied potential constraints in the "BASE" case (normal intact running arrangement), in case scenarios where there were maintenance or contingency outages of a single network element (N-1 case, denoted in our work as "MAINT" or "CONT" case scenarios), or scenarios where there was a contingency that occurred at the same time as a maintenance event ("MAINT + CONT" tagged scenario).

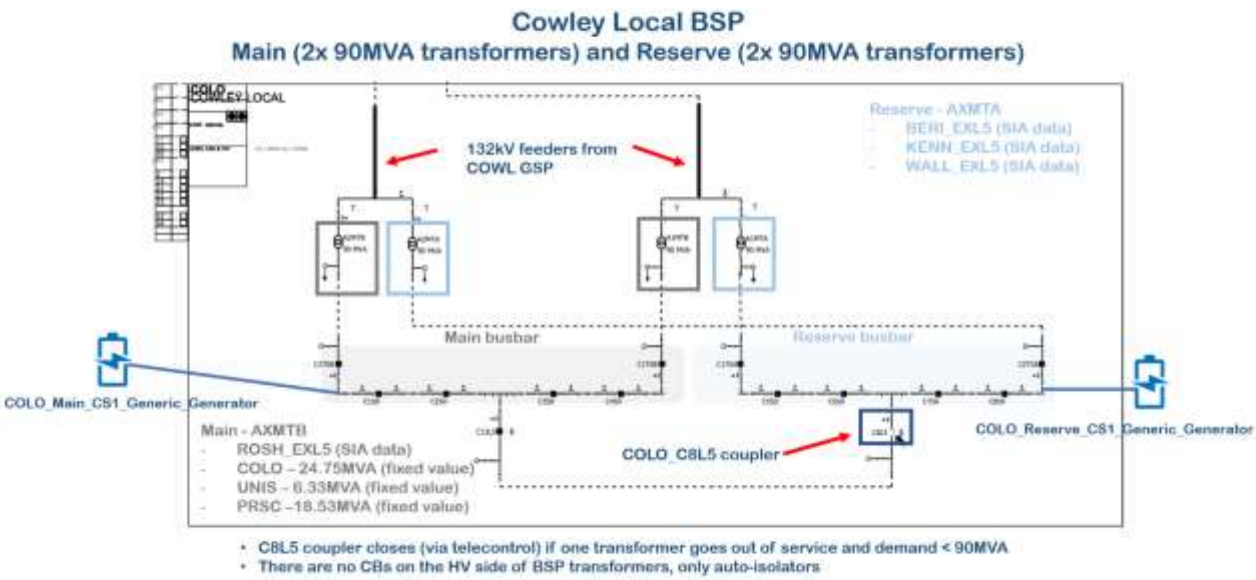

Figure 22: Cowley Local BSP Main and Reserve - Topological layout.

In the BASE case therefore, any potential flex assets connected downstream of this BSP would typically be connected to two transformers in parallel upstream on either side of the BSP Main or Reserve busbars. If there were a single outage in one of the transformers (for either MAINT or CONT scenarios individually), then the same flex asset would be connected to just one remaining upstream transformer. Finally, in cases where the busbar coupler COLO_C8L5 on the 33kV network point was closed, for any reason in support of constraint management in this area, then with all transformers still intact this would result in 4 transformers in parallel upstream of the flex asset. If there was a single maintenance or contingency scenario in this case, it would mean only 3 transformers remain in parallel following the outage.

For a flex asset downstream of these transformers, having 1, 2, 3, or 4 transformers in parallel upstream of it, will tend to divide the impact of any additional flex response from this asset by virtue of Kirchhoff's current laws. All things being equal then, we could expect to see the SFs calculated for some of these flex assets with respect to an individual BSP transformer overload constraint point to be anywhere from:

- ~ 25% or 0.25 (4 transformers in parallel),
- ~ 33% or 0.33 (3 remaining transformers in parallel),
- ~ 50% or 0.50 (two transformers in parallel in the Base case or in a case where the busbar coupler is closed following an N-2 condition and just two transformers remain), or
- ~ 100% or 1.0 (just one transformer upstream, i.e., one transformer on one side of the BP is out of service without the busbar coupler on the 33kV network being closed).

8.1 Case Study A

For this particular Case study, a series of maintenance outages and switching events were simulated in the Cowley Local BSP over 2 different days to illustrate the changes in the SF values, Figure 23 shows the details of these events and Figure 24 illustrates the loading of COLO_A2MTB, highlighting the points where constraints were identified (i.e. loading above the maximum loading threshold).

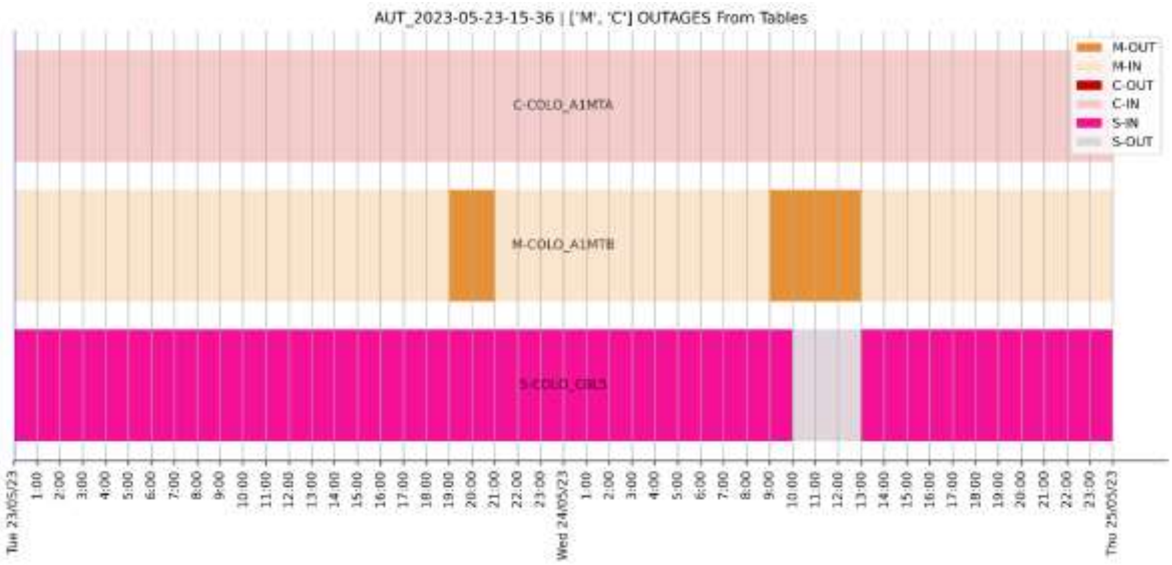

Figure 23: Planned and unplanned outages and switching events during day 1 and day 2

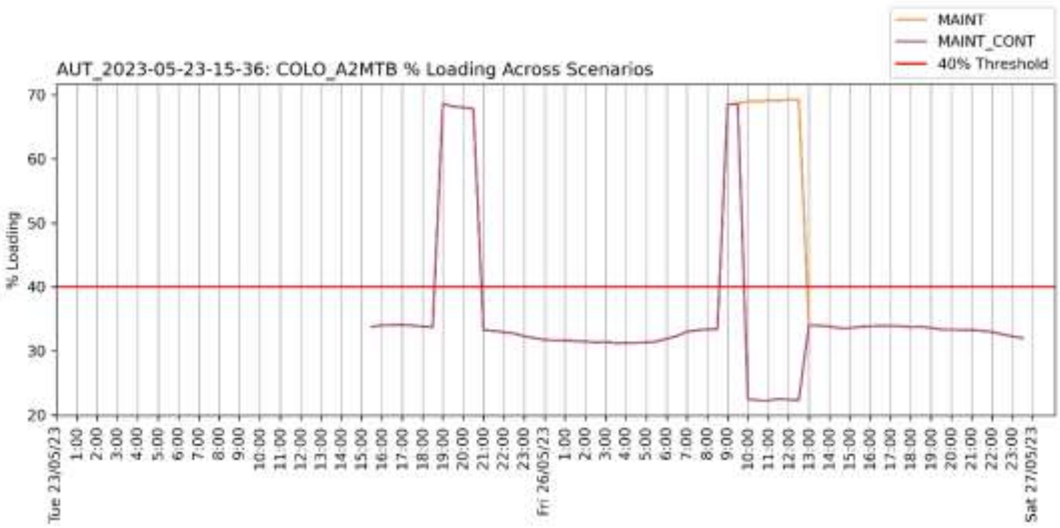

Figure 24: Loading across different scenarios for COLO_A2MTB

Day 1 - Tuesday 23/05/2023 to Wednesday 24/05/2023

Figure 23 shows that for this day COLO_A1MTB goes under maintenance from 09-13hr UTC, there is no change in the status of the busbar coupler COLO_C8L5 (i.e., it remains open).

This means that before any action took place, the 2 sets of transformers in the Main busbar (COLO_A1MTB and COLO_A2MTB) were operating in parallel and any flexibility asset providing power to these would have a SF of ~ 50% or 0.5. When COLO_A1MTB is taken out of service on maintenance, only one transformer remains active in the Main busbar, which means any flexibility asset would have a SF of ~ 100% or 1.0.

Day 2 - Wednesday 24/05/2023 to Thursday 25/05/2023

Figure 23 shows that for this day COLO_A1MTB goes under maintenance from 09-13hr UTC, whereas the busbar coupler COLO_C8L5 is closed from 10-13hr UTC.

This means that before any action took place, the 2 sets of transformers in the Main busbar (COLO_A1MTB and COLO_A2MTB) were operating in parallel and any flexibility asset providing power to these would have a SF of ~ 50% or 0.5. When COLO_A1MTB is taken out of service on maintenance, only one transformer remains active in the Main busbar, which means any flexibility asset would have a SF of ~ 100% or 1.0. However, when the busbar coupler COLO_C8L5 is closed, COLO_A2MTB is paralleled with the Reserve busbar (i.e., COLO_A1MTA and COLO_A2MTA), thus any flexibility asset providing power to these would have a SF of ~ 33% or 0.33.

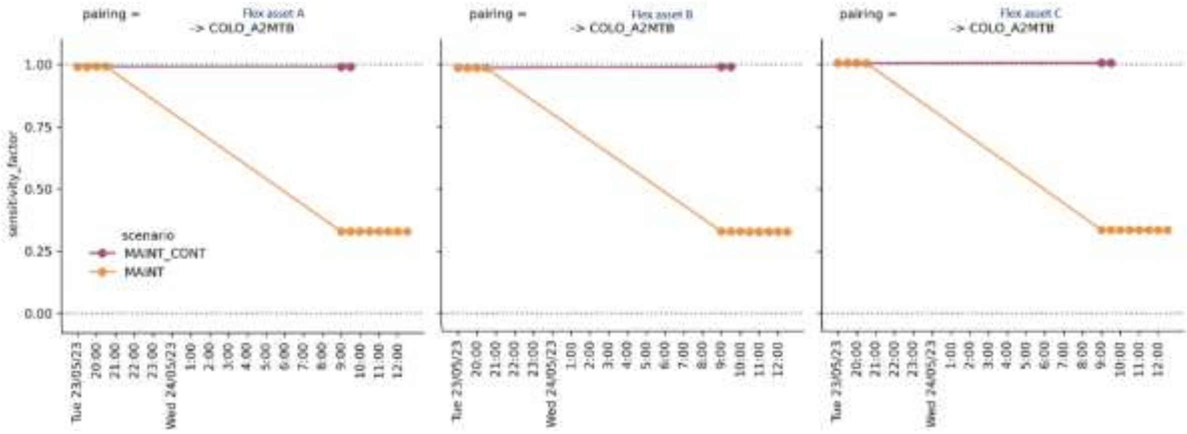

Figure 25: SF results for several flex assets with respect to one of the BSP transformer constraints, across two days

Figure 25 indicates the SF results for several flex assets (which submitted responses/offers) with respect to one of the BSP transformer constraints (COLO_A2MTB) over the two days. One can see that:

- The SF values in the MAINT case for day 1 are remarkably constant (SF=1.0) across the time points (calculated on a half hour basis), which indicates that for a given/fixed topology scenario, there was only minor variation in the SF numerical values across the network loading operating points of the day
- The SF values in the MAINT case for day 2 correspond to a different topological layout and thus the SF decreases to ~ 33% or 0.33 but remains constant across the half hours of interest.

The MAINT_CONT scenario was modelled in a particular way in the TRANSITION trials, where the behaviour of an unknown event was simulated in a “known and controlled” fashion. The outage would only take place once the load flow calculation would match real-time, so as to avoid having a “forecast” of this constraint. For this reason, the SF results are different than the MAINT case.

8.2 Case Study B

This case study looks at the BASE and MAINT scenarios for the Rose Hill Primary, whose topological layout is illustrated in Figure 26. The BASE case has the two transformers in Rose Hill Primary (ROSH_C1MT and ROSH_C2MT) operating in parallel, thus any flexibility asset connected directly downstream from the Primary that provides power to resolve a constraint here would have a SF of ~ 50% or 0.5.

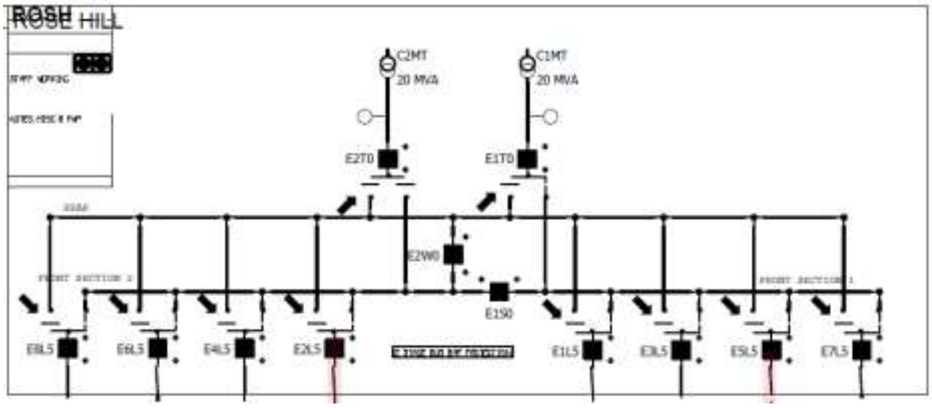

Figure 26: Rose Hill Primary - Topological layout.

Figure 27 shows that ROSH_C1MT goes under maintenance from 18-21hr UTC on Tuesday 18/04/2023. Hence, only one transformer remains in service, which means any flexibility asset connected to the Rose Hill Primary busbar would have a SF of ~ 100% or 1.0 with respect to ROSH_C2MT.

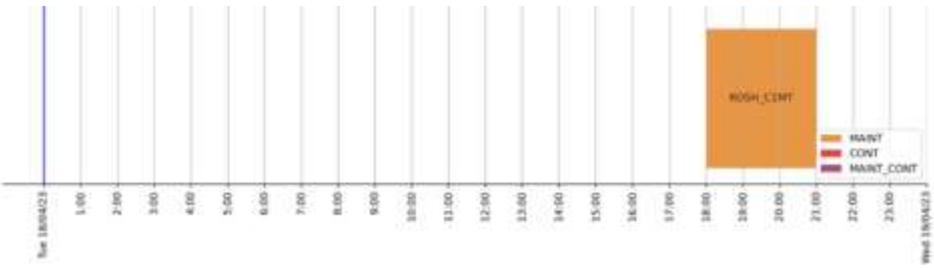

Figure 27: Planned and unplanned outages in Rose Hill Primary

Figure 28 shows how the SF change from one scenario to the other. One can see that:

- The SF value in the BASE case for day 1 (05/04/2023) is very close to 0.5.
- The SF value in the MAINT case for day 2 (18/04/2023) is very close to 1.0 and remains constant through the half hours of relevance.

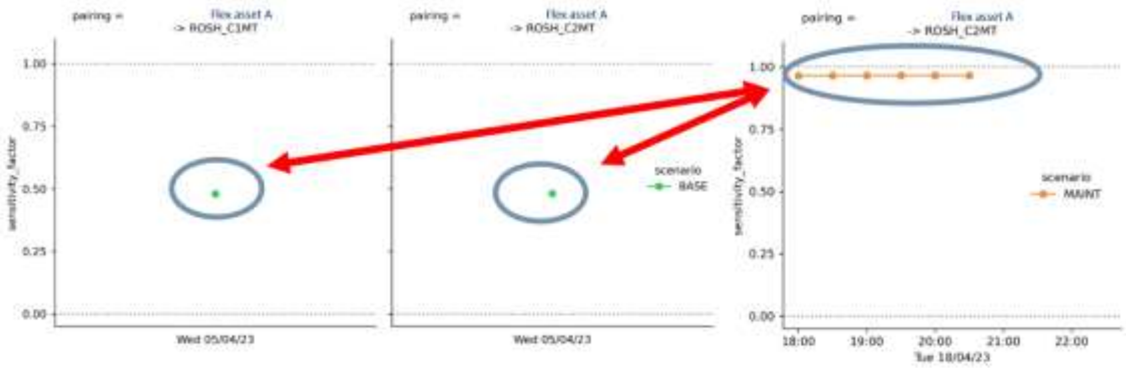

Figure 28: SF results for one flex asset with respect to the transformers in Rose Hill Primary, for two different scenarios (across two days)

9. Appendix A: SF Additional Study Cases

During the SF design process, several study cases are conducted to capture the different effects caused on the NE within the network during the FA implementation. For example, the increase or decrease in loading on lines and transformers, the impact of radial or mesh interconnections, and the effect of line transmission losses, among others. Some of the additional cases were deployed during the development of the SF process detailed in Section 5. Other studies were performed to test and validate the SF methodology. The key findings are described as follows and are included in this report for additional insight and deeper understanding for any practitioners.

9.1 Study Cases Conducted to Help Inform the Design the SF Methodology

9.1.1 Cowley Local BSP

The following three study cases were used to support the final SF methodology detailed in Section 5. The studies mainly investigated how FA can support overloaded NE in radial and mesh interconnection. To this end, the Cowley Local BSP model is employed. The study cases are described below.

- **Case 1:** The flexibility Asset (FA) "SANDFORDHYDRO_HYD_SP5249601797_F" power output varies from 0% to 100% in 10% steps, with Smax=0.4 MVA.

- **Case 2:** The flexibility Asset (FA) "SANDFORDHYDRO_HYD_SP5249601797_F" power output varies from 0% to 100% in 10% steps, with Smax=0.4 MVA, and line "lne_13831_85803_1" length connecting the Kennington Primary Substation is (artificially) changed from 5 km to 30 km.

- **Case 3:** The flexibility Asset (FA) "ROSEHILLCC_DSR_SP5318803371_F" power output varies from 0% to 100% in 10% steps, with an (artificially smaller) Smax=0.055 MVA.

Figure 29, Figure 30 and Figure 31 display the total amount of apparent power in Cowley Local during the three study cases. In all cases, the required apparent power from the network to satisfy the required demand remains constant. It is provided by the external grid representing the GSP and the FA simultaneously.

By looking at the three figures, as the FA power output increases, the power output from the external grid decreases. This is completely expected since the prime objective of employing FA is to reduce the power injection from the GSP, and thus alleviate congested zones or elements within the network. This effect is more prominent in Case 1 (Figure 29) due to the FA's size, location and interconnection. Particularly, because SANDFORDHYDRO_HYD_SP5249601797_F is connected directly to the LV side of the Kennington Primary transformer, which is radially connected to the LV side of Cowley Local. So, the impact of injecting active power in the downstream part of the network is directly reflected upstream, resulting in less MVA provided by the GSP.

Nevertheless, the benefits of having a radial interconnection can be affected by the length of the transmission line. For example, Case 2 is affected by the transmission losses in Line _13831_85803_1 (length 30 km), which are six times larger than Case 1 (length 5 km), resulting in higher MVA produced by the External Grid to meet identical demand than Case 1. Due to the size of FA in Case 3 (i.e., 0.055

MVA) and, therefore its total power injection within the network, most of the MVAs in this case are generated by the external grid as depicted in Figure 31. Still, all three cases show the potential contribution of the FA power injection regarding the power output from the GSP.

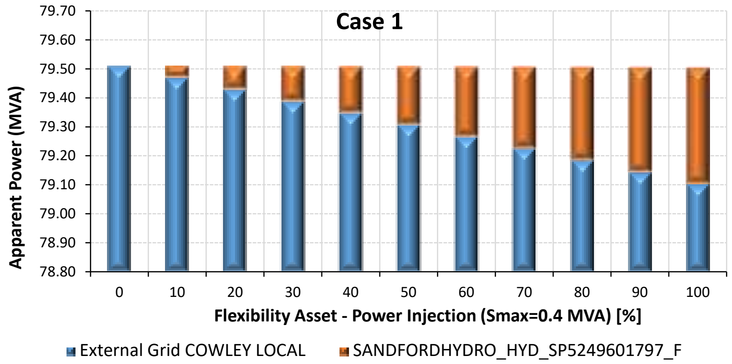

Figure 29: Total amount of apparent power required in Cowley Local during study Case 1

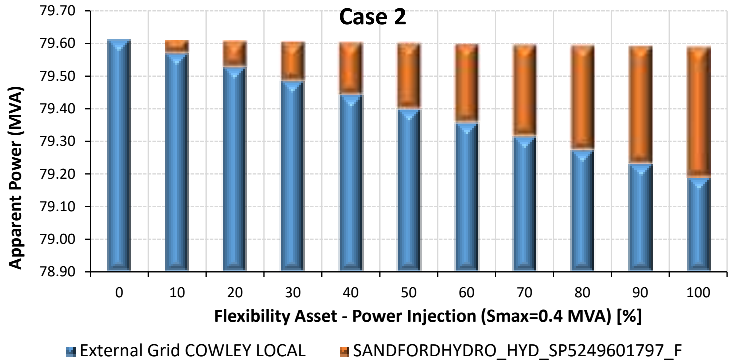

Figure 30: Total amount of apparent power required in Cowley Local during study Case 2

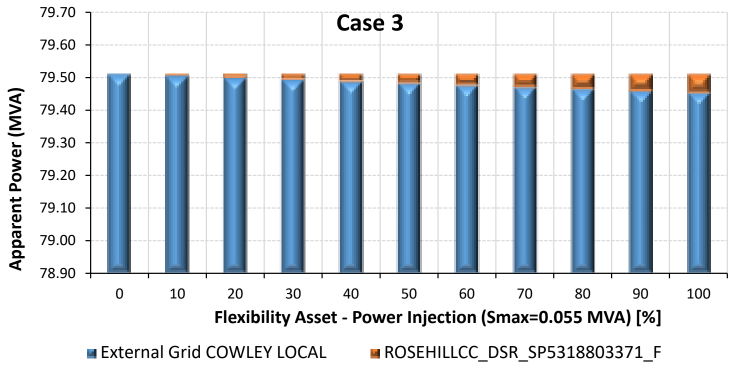

Figure 31: Total amount of apparent power required in Cowley Local during study Case 3

Figure 32 and Figure 33 illustrate the effect on loading captured in MVA in the BSP and Primary transformers characterised by COLO_A1MTB/A2MTB and KENN_C1MT, respectively, for study cases 1 and 2. Case study 3 involving BSP transformers COLO_A1MTA/A2MTA and the Primary transformers ROSH_C1MT/C2MT is depicted in Figure 34.

As the three figures show, the power injection from the FA reduces the transformer's loading in all cases. The effect is more prominent in Case 1 because Case 2 is affected by the transmission losses that occurred downstream of the BSP transformers. The impact on the BSP transformers from Case 3 is very low since the downstream Rose Hill interconnection is more mesh than Kennington (i. e. Case1 and 2) so the power injection from ROSEHILLCC_DSR_SP5318803371_F is more distributed within the network. Still, the reduction in MVAs is virtually identical among the BSPs and Primary Substations transformers in parallel, as in the case of Colo_A1/A2_MTA/B and ROSH_C1/C2_MT, respectively.

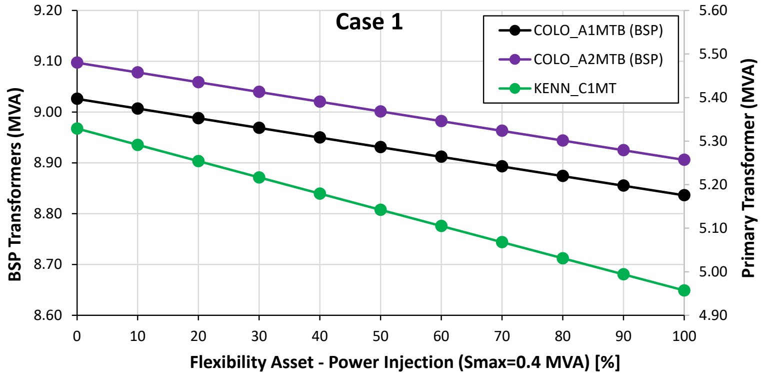

Figure 32: BSP and Primary Transformers loading in MVA during study Case 1

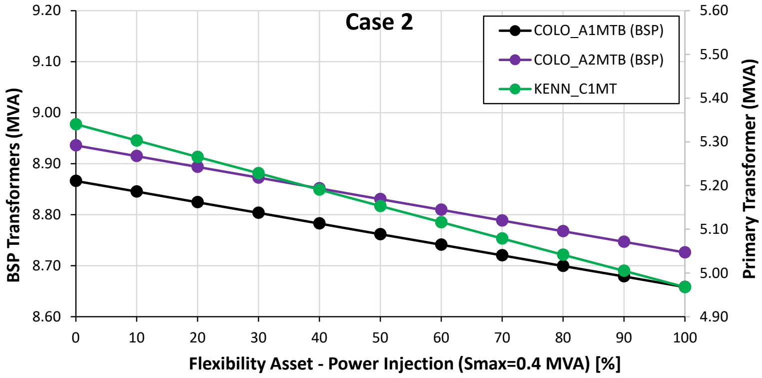

Figure 33: BSP and Primary Transformers loading in MVA during study Case 2

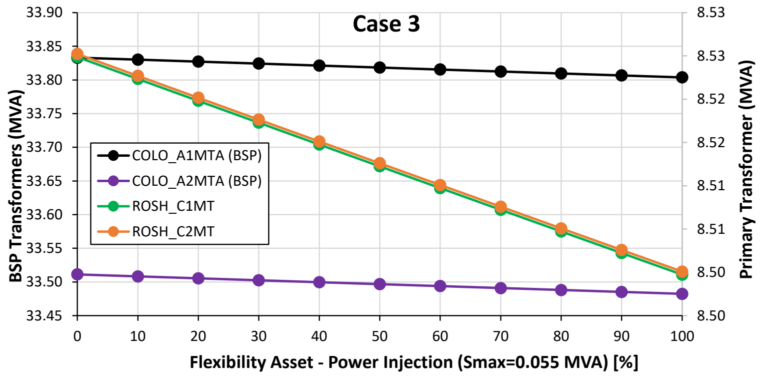

Figure 34: BSP and Primary Transformers loading in MVA during study Case 3

Figure 35, Figure 36 and Figure 37 illustrate the SF calculations obtained for the BSP and Primary transformer during the study cases 1, 2 and 3, respectively. It is essential to mention that at this stage during the SF development, the NE's power change with respect to the FA power injection is captured slightly differently than the final process described in Section 5. Within this context, the NE (i.e., transformers) Delta Flow is defined as the change in the assets' power flow (MVA) when one power injection step from the FA (i.e., 10%*FA_Smax) is inserted into the system.

The delta flex is defined as the cumulative injection of MVA from the FA from 0 to Smax with a 10% apparent power increase in each step. Instead, if the change in MVA for each step from the FA is used (e.g., from 10% to 20%), as in the case of Delta Flow, Delta Flex becomes constant because the increase is always 0.04 MVA.

The power injection from the FA in all the cases is virtually constant (i.e., 10% increase). However, the most considerable impact is seen in the first step due to Delta Flex being minimum. Thus, as expected in all the other cases, the total Delta Flow/Delta Flex decreases as Delta Flex increases since FA reaches its maximum output.

Case 1 (Figure 35) and 2 (Figure 36) show the maximum increase in Delta Flow occurs in the Primary Substation transformer (KENN_C1MT) since there is a radial interconnection with the FA connected downstream Kennington. Both cases produce virtually identical flows. However, the BSP transformers in Case 2 are slightly more loaded than in Case 1, mainly due to more power being produced by the External Grid to compensate for the transmission losses in line Line _13831_85803_1. Still, as both cases are modelled as a radial network, the power flows are proportionally distributed among the two BSP transformers. Case 3 (Figure 37) represents a more mesh interconnection upstream of the Rose Hill Primary Substation. As expected the FA power injection is proportionally split among both BSP and Primary Substation transformers.

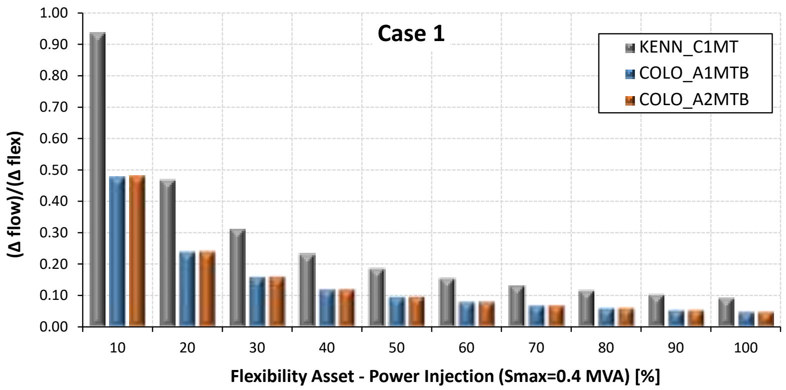

Figure 35: SF calculations on BSP and Primary transformers during study case 1

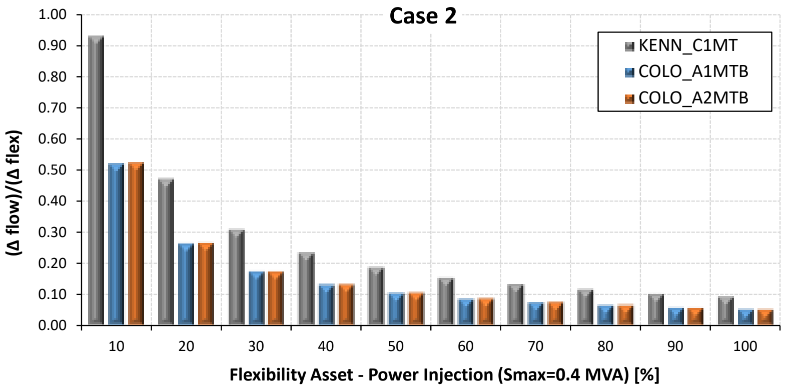

Figure 36: SF calculations on BSP and Primary transformers during study case 2

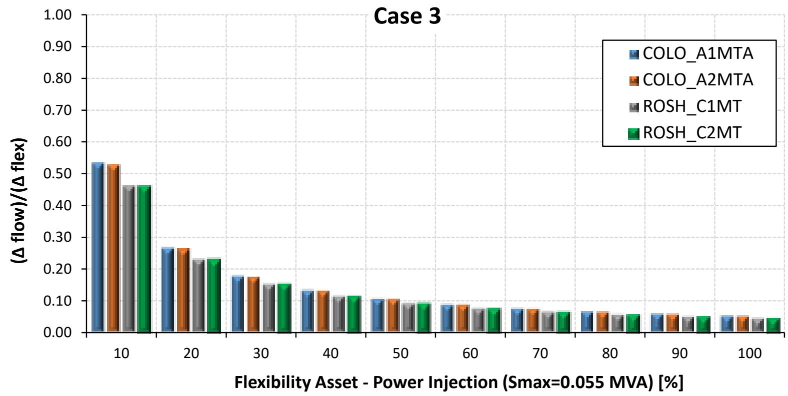

Figure 37: SF calculations on BSP and Primary transformers during study case 3.

The lines loading at 132 kV and 33 kV with respect to the FA power injection during the study cases 1, 2 and 3 are depicted in Figure 38, Figure 39 and Figure 40, respectively. It is worth mentioning that in some of the cases some lines are overlapped in the figures.

In all three cases, as the FA power injection increases, the line loading decreases. This shows the contribution of FA could have to alleviate the overloaded lines. Case 2 shows 33 kV line is less loaded than the same line in Case 1, caused mainly by the excessive amount of transmission losses generated by the 50 km transmission line (lne_13831_85803_1), which is six times larger. As the FA in Case 3 is more afar from the Primary feeder head, the effect on the BSP and 33 kV lines is minimal.

To summarize, further studies are required to obtain more solid conclusions regarding the impact of implementing FA within the network. Particularly studies that help to understand better the meaning of Delta Flow/Delta Flex values, the location, the size and interconnection (i.e., radial/mesh) of the FA within the network.

Still, as the preliminary conclusion, FAs could help to support the network operation by reducing, alleviating or removing the lines or transformer's exceedances. Also, the size, location and FA interconnection within the network play a significant role, which needs further investigation. No major impact is found on the network voltage performance.

Finally, it is important to stress that these are the first study cases deployed for building SF metrics and evaluating their applicability within the network constraint analysis. At this stage, these studies provided an insight into the SF impacts on the network, but more importantly the foundation for the final SF process described in Section 5.

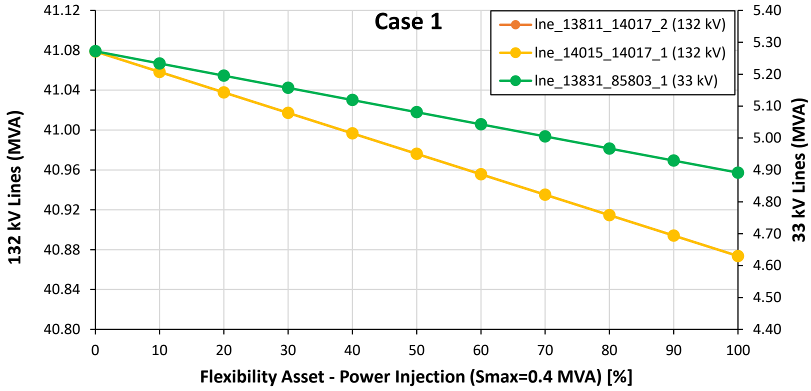

Figure 38: Lines at 132 kV and 33 kV loading in MVA during study case 1

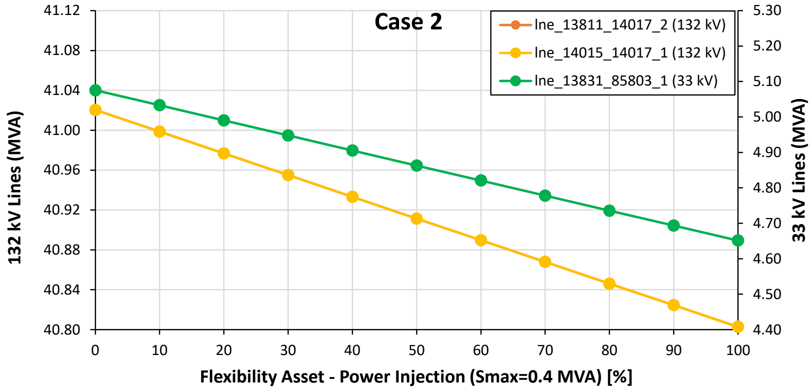

Figure 39: Lines at 132 kV and 33 kV loading in MVA during study case 2

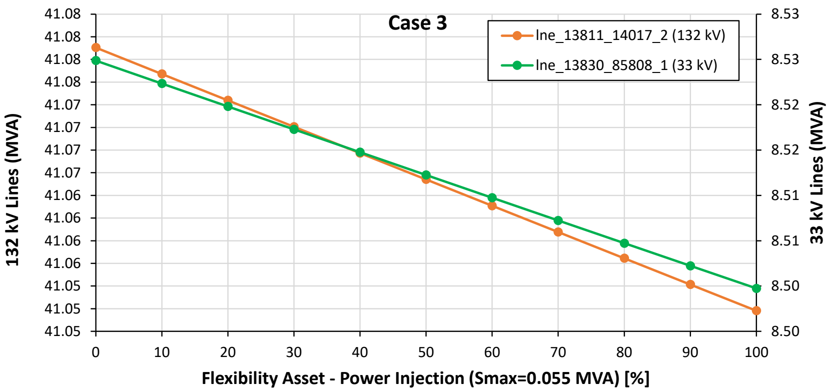

Figure 40: Lines at 132 kV and 33 kV loading in MVA during study case 3

9.1.2 Witney Yarnton BSP

The following four study cases are also used to support the final SF methodology detailed in Section 5. In this case, the Witney Yarnton BSP model is utilized mainly to investigate the effect of a mesh network during a FA implementation. The four cases are divided into two main study cases, namely, Case A and B. Case A involves the Chipping Norton Primary substation, whereas Case B includes the Eynsham Primary substation. The study cases are described below.

9.1.2.1 Case A

Case A aims to demonstrate the impact of an N-1 topology change on the SF calculations. So the business as usual (BAU) is defined as FA located at Chipping Norton Primary contributing to both Witney and Yarnton BSPs. The N-1 study occurs when the link between the single 33 kV line connecting Kiddington Primary KIDD-C to Charlbury Primary CHAR-C1T is broken (i.e., line lne_13131_17830_1 is out of service). Case A is displayed in Figure 41.

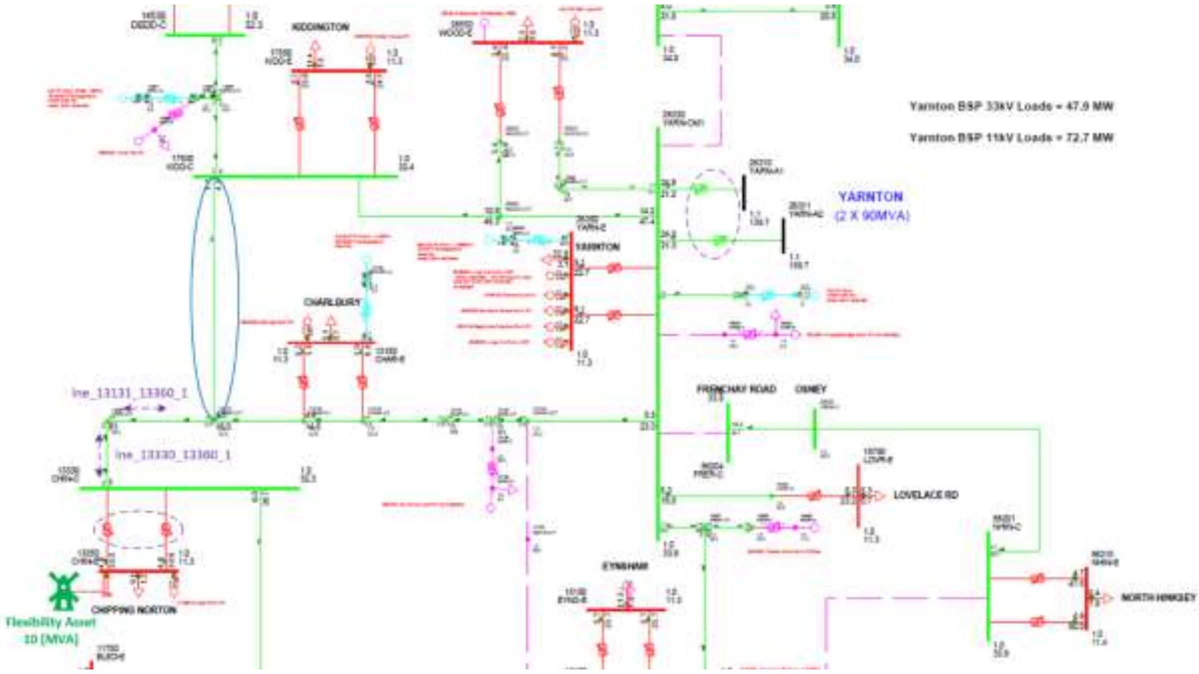

Figure 41: Network model with a FA located at Chipping Norton contributing to both Witney and Yarnton BSPs

The FA during BAU power output varies from 0% to 100% in 10% steps, with Smax=10 MVA at Chipping Norton Primary contributing to both Witney and Yarnton BSPs. Figure 42 shows the active power in transformer CHIN_C1MT and its loading level during the FA's different power injection steps. The blue bars describe the MW and refer to the left-hand side vertical axis values. The loading is defined by the black line with red dots and entails the right-hand side vertical axis values. The horizontal axis depicted the different active power injection steps from the FA.

As Figure 42 displays the CHIN_C1MT active power flow (blue bars) decreases from steps 1 to 8. In fact, during step 9 the MW are close to zero, which is reflected by the 2% loading. This makes perfect sense since the FA is mainly used for satisfying the local demand at Chipping Norton and thus less active power is coming from upstream (i.e., Witney or Yarnton BPSs) resulting in a decrease in loading. However, as Figure 42 shows, there is a change in the power flow direction in CHIN_C1MT at step 10, reflected by the negative MW. This can be explained by the surplus of MW generated at the LV side of transformer CHIN_C1MT going to the HV side when generation from the FA (i.e., step 10, and Pout=10 MW) exceeds the local demand in Chipping Norton, and thus a reverse power flow occurs. This phenomenon is also captured by the loading at step 10 (black line), which starts to increase due to more MW flowing from the LV to the HV side of the transformer to feed demand in Witney or Yarnton BPSs.

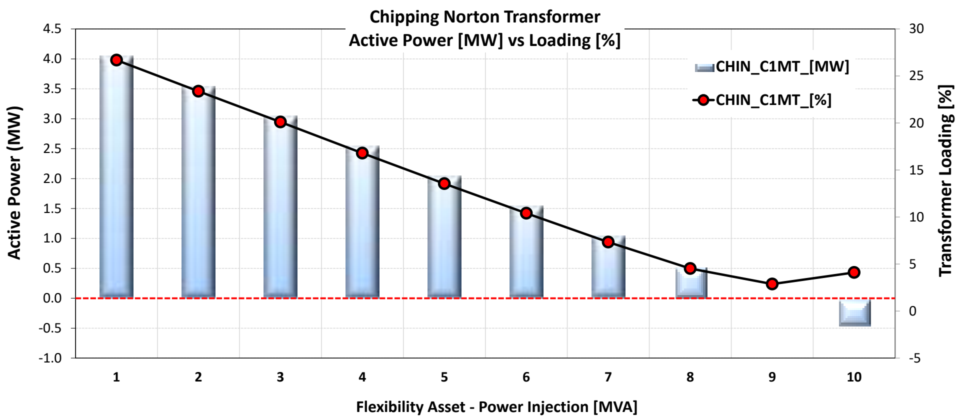

Figure 42: Case A - Chipping Norton Primary transformer active power vs loading

Figure 43 illustrates the SF calculations of four different and parallel transformers from the Witney Yarnton network model. Particularly, two parallel BSP transformers YARN_A2/A1_MT and WITN_A1/A2_MT and two parallel Primary transformers CHIN_C1/C2_MT and CHAR_C1/C2_MT. A comparison of the change in power in both scenarios (i.e., BAU and N-1) is performed considering only two steps, namely, FA power output from 90% to 100% with Smax=10 MVA. The single 33kV line out of service connecting Kiddington Primary KIDD-C to Charlbury Primary CHAR-C1T is described by the blue oval in Figure 41.

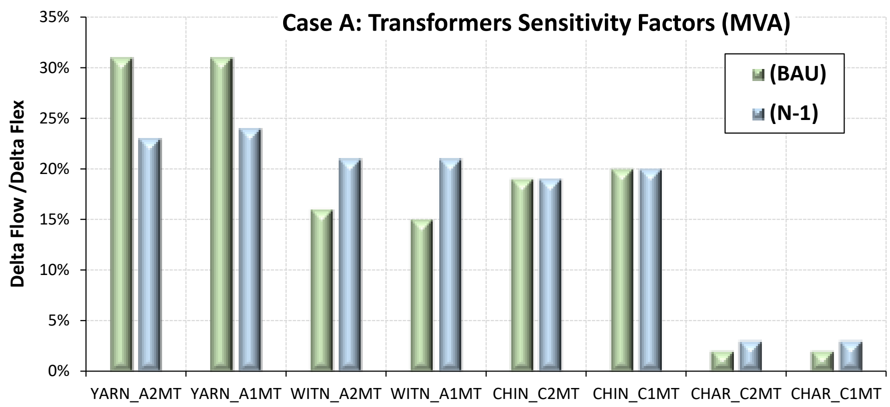

Figure 43: Case A – SF of different Witney Yarnton transformers

By looking at Figure 43, it can be concluded that Yarnton BSP transformers (i.e., YARN_A1/A2_MT) are the most significant contributor to satisfying Chipping Norton demand. In particular, due to the highest change in loading occurs in these two parallel transformers during the FA power injection in the BAU case. However, the highest power flow variation during the N-1 case (i.e., lne_13131_17830_1 out of service) happens in the Witney BSP transformers (i.e., WITN_A1/A2_MT), as shown in Figure 43. This can be explained because once the link connecting Kiddington Primary KIDD-C to Charlbury Primary CHAR-C1T is broken, Witney BPS transformers are responsible for meeting Chipping Norton demand.

Table 9 listing the SF indexes help to understand better the effects happening in both cases. The SF from YARN_A1/A2_MT are reduced from BAU to N-1. On the other hand, the SF from WITN_A1/A2_MT are increasing. Consequently, under normal operating conditions the required generation at Chipping Norton is provided via Yarnton transformers. This is replaced by the generation coming from the upstream Witney BSP transformer during contingency events. In either case, it is clear that the power injection from the FA at 11 kV has the potential to influence the active power flows in the BSP transformers.

In addition, as expected since the FA is connected directly to the Chipping Norton substation the SF from CHIN_C1/C2_MT remain unchanged during both cases. A negligible variation occurs in both Charlbury transformers. Thus, the findings from Figure 43 and Table 9 show the potential contribution that FA could have in reducing the power flows in upstream NE, and its capability to support the network performance during lines or transformers' thermal constraints.

Table 9: Case A- SF comparison between BAU and N-1

Transformer Name	(BAU)	(N-1)
	SF	SF
YARN_A2MT	0.31	0.23
YARN_A1MT	0.31	0.23
WITN_A2MT	0.15	0.21
WITN_A1MT	0.15	0.21
CHIN_C2MT	0.19	0.19
CHIN_C1MT	0.19	0.19
CHAR_C2MT	0.02	0.03
CHAR_C1MT	0.02	0.03

Based on Case A, we can draw two important conclusions. Firstly, alterations in the network topology can lead to sudden changes in computed SF values. Secondly, the power output of a flex asset can cause the MVA to flow in the opposite direction in a network element. Therefore, we need to use an unnatural +/- sign convention for MVA results to accurately capture such variations and prevent any misleading SF calculations.

9.1.2.2 Case B

Case B aims to demonstrate the impact of network reconfiguration on the SF calculations. Eynsham Primary is typically connected to Yarnton BSP via a 33kV line, however, there is also a NOP to Witney BSP that is usually open. Additionally, there is an ACO scheme that operates when the line between EYNS-C 33kV terminal and the Yarnton-CM1 terminal is lost, meaning there is an automatic close of the NOP between EYNS-C and WITN-C terminal. The idea is to understand the SF of a FA connected at Eynsham Primary to Yarnton and Witney BSPs, both before and after this reconfiguration. So BAU is defined as the FA at Eynsham Primary contributing to Witney BSP. The N-1 is when the FA at Eynsham Primary is contributing to Yarnton BSP. Case B is depicted in Figure 44.

Figure 45 depicts the SF calculations of a set of three parallel transformers from the Witney Yarnton network model. Particularly, two parallel BSP transformers YARN_A2/A1_MT and WITN_A1/A2_MT and one parallel Primary transformers EYNS_C1/C2_MT. A comparison of the change in active power flow of these transformers during BAU and N-1 is conducted and displayed in Figure 45. As in Case A, only two steps of power injection from the FA are considered. Namely, FA power output from 90% to 100% with Smax=10 MVA. The blue oval describes the NOP between EYNS-C and WITN-C terminal in Figure 44.

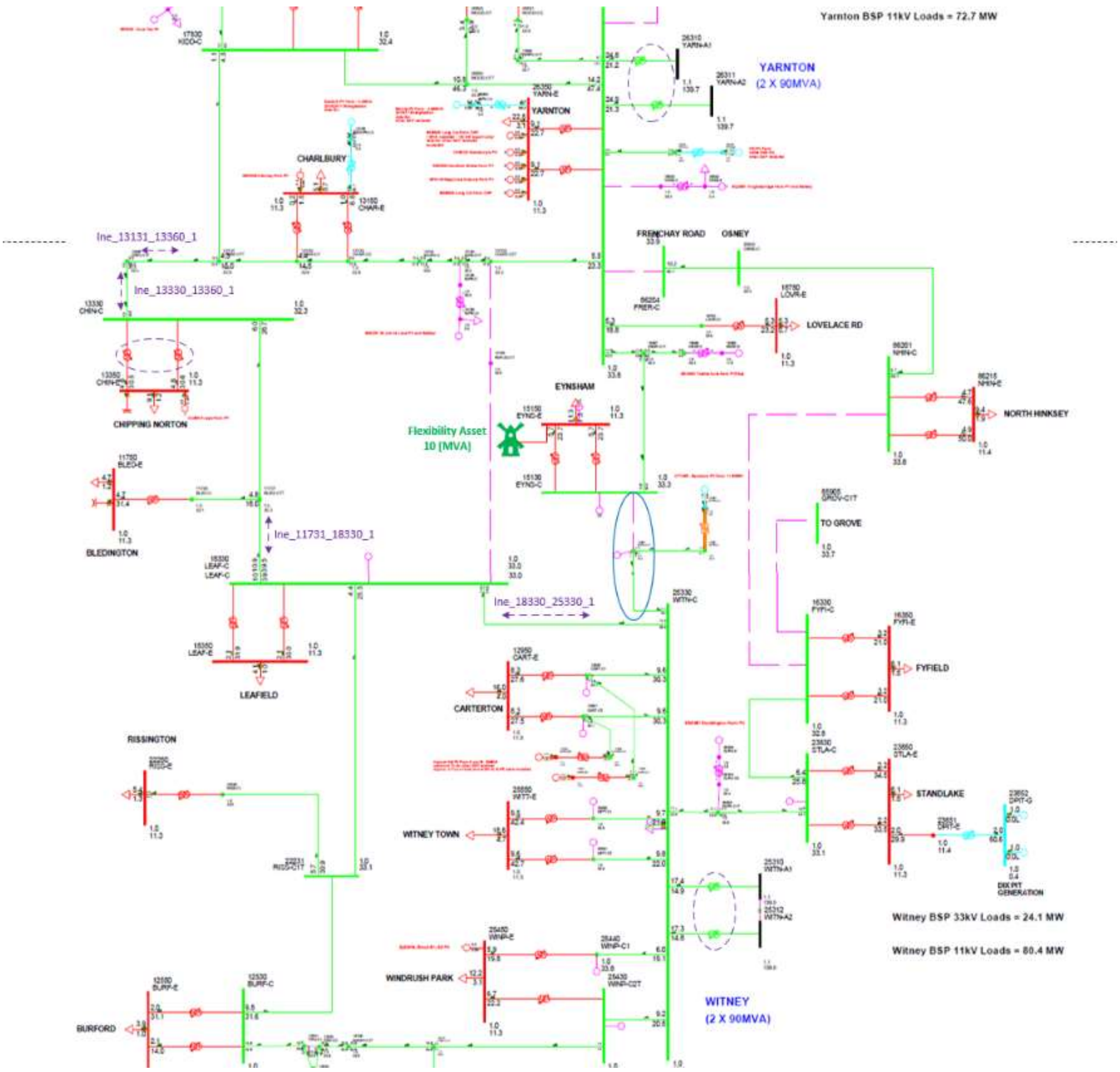

Figure 44: Network model with a FA located at Eynsham Primary contributing to both Witney and Yarnton BSPs

As shown in Figure 45, the highest variation in the active power flow occurs in WITN_A1/A2_MT transformers during the BAU since the Eynsham Primary FA contributes directly to Witney BSP via NOP lne_15060_15130_1. In the N-1 case, the Eynsham Primary FA contributes directly to Yarnton via lne_15067_15130_1, so greatest deviations happen in YARN_A1/A2_MT transformers. These results are entirely expected because of the single interconnection between Eynsham and Yarnton or

Eynsham to Witney, meaning any generation surplus from the FA directly impacts both BSP transformers.

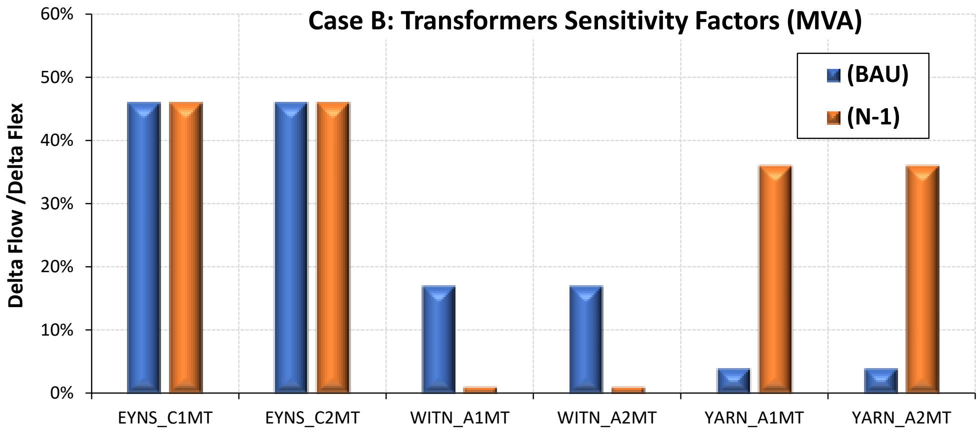

Figure 45: Case B – SF of different Witney Yarnton transformers

Table 10 describes the SF of the six transformers shown in Figure 45. It is clear from the table that SF calculations are highly dependent on the network topology, so they do not remain fixed during network reconfiguration. These effects can be seen from the reduction or increase in the SF index in all four BSP transformers (i.e., WITN_A1/A2_MT and YARN_A1/A2_MT) when the NOP closes.

Additionally, the mesh network topology from Witney Yarnton BSP plays a key part in computing the SF index and, thus, FA impact within the network. Primarily, in a mesh network the power flow goes anywhere searching for the lowest line impedance, to satisfy the network demand or to avoid congested paths, among others. As a result, understanding the different changes in power flow happening in any NE during FA power injection and its SF index becomes significantly challenging. For example, according to Table 10 in BAU the change in power flow caused by the surplus generation produced in Eynsham is more prominent in WITN_A1/A2_MT with SF=0.17. Still a small effect can be seen in YARN_A1/A2_MT, because of line lne_18330_25330_1 supplying Yarnton BSP, despite an existing direct interconnection between Witney and Yarnton BSPs.

Table 10: Case B - SF comparison between BAU and N-1

Transformer Name	(BAU)	(N-1)
	SF	SF
EYNS_C1MT	0.46	0.46
EYNS_C2MT	0.46	0.46
WITN_A1MT	0.17	0.01
WITN_A2MT	0.17	0.01
YARN_A1MT	0.04	0.36
YARN_A2MT	0.04	0.36

9.2 Study Cases to Test the Concluded SF Methodology

9.2.1 Cowley Local BSP

The following two study cases were used to validate the SF methodology detailed in Section 5. However, these studies are categorized as Edge Cases since they only happen during a particular set of operating scenarios. Within this context, the cases were mainly used to understand better the numerical SF values obtained during the application of the SF methodology.

The two cases referred to an export condition producing a network constraint where the power flow direction comes from the downstream to the upstream side of the network. So, the aim is to revolve the operational constraint by decreasing or increasing the generation or demand downstream of the affected NE, respectively.

During the studies, it is assumed that the network topology remains unchanged, that FAs reduce or increase active power injection during normal operation conditions (i.e., no failures). However, these particular cases considered a significant level of reactive power injection with respect to their active power penetration. As a result, SF calculations are significantly affected.

The edge cases occurred in two substations. Particularly, in Kennington and Rose Hill Primary Substations, which are depicted in Figure 12 and Figure 13, respectively. The FA SANDFORDHYDRO_HYD_SP5249601797_F with Pmax=0.4 MW located in Feeder KENN_E6L5 is used for solving the network constraint in transformer KENN_C1MT. The FA ROSEHILLCC_DSR_SP5318803371_F with Pmax=0.315 MW located in Feeder ROSH_E2L5 is utilized for removing the network constraint in transformer ROSH_C1MT.

Figure 46 shows the loading effect in MW of transformer KENN_C1MT during an export constraint when the FA (i.e., Sandfordhydro_F) reduces the power injection. The vertical axis P_LV [MW] refers to KENN_C1MT loading, defined by the orange bars. The second vertical axis characterised by *Pflex* [MW] involves the active power output from the FA, and the blue lines represent it. The Horizontal axis defines the FA power injection steps (i.e., 11) used for managing the constraint in KENN_C1MT.

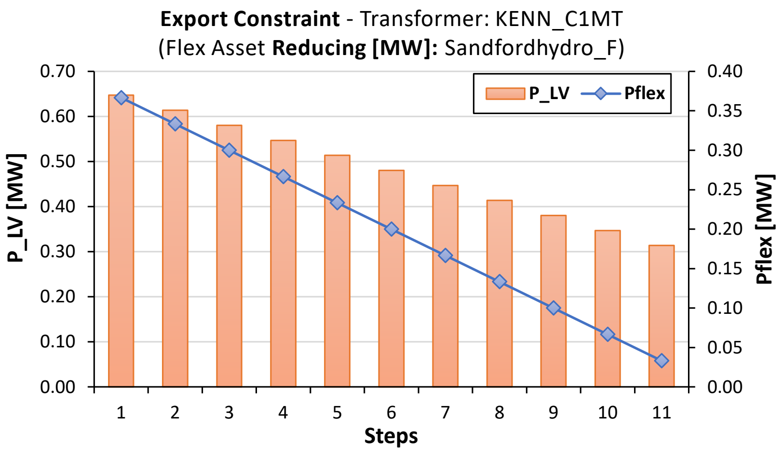

Figure 46: Export Case - Active power loading of transformer KENN_C1MT when FA reduces active power injection – Edge Case

Figure 46 illustrates that as *Pflex* reduces the power injection in each step, the loading in KENN_C1MT P_LV is also reduced, and thus the export constraint on transformer KENN_C1MT. Thus, as expected by reducing the MW contribution from Sandfordhydro_F a drop in the generation surplus in 85814 KENN-E-S1 is produced, and so a decrease in the export constraint.

The results from Figure 18 and Figure 46 look virtually identical. Despite the differences in the overloading level in KENN_C1MT, the reduced power (i.e., MW) in both cases is roughly the same 0.35 MW. This makes perfect sense due to the radial interconnection of Sandfordhydro_F to KENN_C1MT.

Nevertheless, the SF indexes listed in Table 11 significantly differ from the ones obtained in Table 5 (highlighted in blue in Table 11). As pointed out in Figure 46, P_LV decreases as the FA power injection decrease in each step, resulting in a reduction in S_LV as displayed in row 4 (Table 11). This effect can also be observed in the decrease in loading shown in row 7 from Table 11.

However, it is important to remember that SF is defined as $\Delta Flow\ [MVA]$ divided by $\Delta Flow_k\ [MW]$ as described in Section 5. In this case, $\Delta Flow_k\ [MW]$ is identical to the variation obtained in Table 5, but $SF\ [MVA]/[MW]$ at each step is substantially smaller. This phenomenon is rather strange since the network remains unchanged, so a SF of 0.9 [MVA]/[MW] should also be expected in this case.

Based on the current knowledge gained during the development of the SF methodology so far, this edge case can be explained by the following aspects.

Row 7 in Table 11 shows the level of loading in transformer KENN_C1MT, which is calculated based on the maximum current in kA flowing through the transformer. This loading level is very low and it is primarily governed by the MW contribution produced by the FA injected power from the LV to the HV side of KENN_C1MT. This is reflected in row 6. On the other hand, since the FA injects MW only, the amount of reactive power through the transformer KENN_C1MT remains fixed at each step (row 5), and it is at least roughly 3.5 times larger than injected MW. Consequently, the highest contribution to the $\Delta Flow\ [MVA]$ at each step is the MVAr displayed in row 5, which is approximately identical to the MVAs in row 4 due to the small portion of MW flowing through the transformer. As a result, the SF parameters shown in row 3 are correct based on the application of the SF methodology, but the high MVAr and low MW ultimately govern these values at each step flowing through KENN_C1MT.

Table 11: Export Case - SF calculations of KENN_C1MT during FA active power reduction – Edge Case

1	**FA Steps**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
2	**SF [MVA]/[MW]***	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
3	**SF [MVA]/[MW]**	0.28	0.27	0.27	0.26	0.25	0.25	0.24	0.23	0.23	0.22	0.21
4	**S_LV [MVA]**	2.347	2.339	2.330	2.322	2.314	2.307	2.301	2.294	2.289	2.283	2.279
5	**Q_LV [MVAr]**	2.257	2.257	2.257	2.257	2.257	2.257	2.257	2.257	2.257	2.257	2.257
6	**P_LV [MW]**	0.647	0.614	0.580	0.547	0.514	0.480	0.447	0.414	0.380	0.347	0.314
7	**Loading [%]**	16.081	16.021	15.964	15.910	15.859	15.811	15.766	15.724	15.686	15.651	15.619

*Result from Table 5

A similar situation occurred in Rose Hill Primary Substations during an export constraint. Figure 47 shows the results of an export constraint that occurred in Rose Hill Primary Substation (Figure 13). Particularly, in one of the two parallel transformers feeding Terminal 85817 ROSH-E-S1, namely, transformer ROSH_C1MT. Figure 47 illustrates that as *Pflex* increases the power consumption, i.e., increase in demand, the loading in P_LV is reduced. This can be explained due to the overall demand on Rose Hill being increased mainly by the FA and, thus, less surplus of active power is produced in Terminal 85817 ROSH-E-S1, resulting in fewer MW flowing through ROSH_C1MT.

The effect of increasing the power injection from ROSEHILLCC_DSR_F in Figure 20 and Figure 47 is the same, meaning a reduction in P_LV of roughly 0.15 MW is achieved. This reduction is based on the FA Pmax injected through both parallel ROSH_C1MT/C2MT transformers.

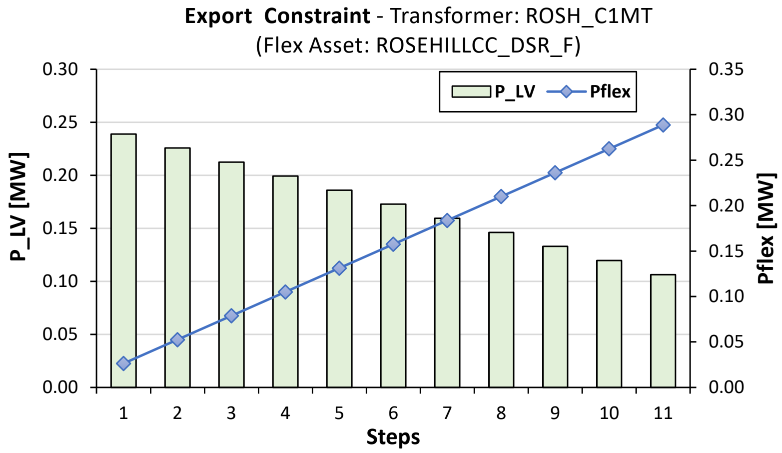

Figure 47: Export Case - Active power loading of transformer ROSH_C1MT when FA increases active power injection – Edge Case

Nevertheless, the SF indexes listed in Table 12, rows 2 and 3 are completely different. In fact, the SF from this edge case is nearly zero. The main reason for this is the low active power flow (row 6) in ROSH_C1MT, also reflected in row 7 at each step compared to the reactive power demand (row 5) from the transformer ROSH_C1MT. Consequently, the SF $\Delta Flow\ [MVA]$ variations from ROSH_C1MT with respect to ROSEHILLCC_DSR_F (i.e., FA) at each step are purely controlled by the MVAr required in Terminal 85817 ROSH-E-S1. This effect can be seen by comparing the results from rows 4 and 5, which are virtually identical.

Table 12: Export Case - SF calculations of ROSH_C1MT during FA active power injection – Edge Case

1	**FA Steps**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
2	**SF [MVA]/[MW]***	**0.43**	**0.43**	**0.43**	**0.43**	**0.43**	**0.42**	**0.42**	**0.42**	**0.42**	**0.42**	**0.41**
3	**SF [MVA]/[MW]**	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03
4	**S_LV [MVA]**	4.317	4.317	4.317	4.317	4.318	4.319	4.320	4.321	4.322	4.324	4.326
5	**Q_LV [MVAr]**	4.311	4.311	4.312	4.313	4.314	4.315	4.317	4.318	4.320	4.322	4.325
6	**P_LV [MW]**	0.239	0.226	0.212	0.199	0.186	0.173	0.159	0.146	0.133	0.120	0.106
7	**Loading [%]**	22.821	22.820	22.820	22.822	22.825	22.830	22.835	22.843	22.851	22.862	22.873

*Result from Table 7

Hence, the following can be concluded by looking at both edge cases described above and their counterparts described in Section 6.1.2.

- The application of the SF methodology from Section 5 works in all cases. However, the SF index treated as single variable for determining the contribution of a FA for solving a constraint can be misleading. So extra electrical parameters such as active power, reactive power and level of loading need to be also considered for a better understating of a FA performance with respect to a NE.

- The amount of reactive power flowing through a NE can significantly affect the SF index calculation. Particularly, if the NE has a low level of utilisation and active power consumption. However, it is important to mention that any constrained element should have a high level of current kA and, therefore, active power MW flowing through it, so unless a large amount of reactive power MVAr demand is required downstream of the constrained element, this case is unlikely to occur.

- One FA could generate a different SF index for an identical element as seen in the edge cases. Indeed, as discussed substantial differences could occur. Thus, it is significantly relevant to stress that SF calculations rely on specific operational scenarios and set points, so having a low or high SF index at any moment in time, i.e., t=1 does not guarantee an identical FA performance with respect to the same element at t=2.