Imperial College London

# Power Potential project

# Evaluating Synergies and Conflicts of DER Services for Distribution and Transmission Systems and Market Power Assessment

Goran Strbac, Danny Pudjianto,
Predrag Djapic

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# Acknowledgements

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# Extended Executive Summary

Power Potential is a novel techno-economic framework designed to provide opportunities for distributed energy resources (DERs) to offer reactive power capability and voltage control services in the South East area of Great Britain's transmission system. In this region, demand for these services has increased in the past several years due to the rapid growth of DERs, new interconnection links, and reduced operating hours of large-scale conventional generation units as traditional sources. By enabling the provision of voltage control services by DERs, the need for investment in traditional transmission level reactive resources (e.g. Static VAR Compensators (SVCs), shunt capacitors/reactors) or engaging out-of-merit generation will be reduced, leading to lower costs to customers.

Although the current focus of the trial is to use DER reactive services to support transmission while respecting distribution network constraints, in principle, the Power Potential framework enables DERs to provide network services to support not only the Great Britain (GB) Electricity System Operator (ESO) but also to the local Distribution System Operator (DSO). DERs can provide an alternative lower-cost solution to the network reinforcement needed to solve network problems faced by both the ESO and DSO. As DERs can serve both the ESO and DSO, it is vital that the control and commercial frameworks used to allocate DER services for the ESO and DSO do not trigger conflicts between the system operators. Instead, DERs can be used to solve the ESO and DSO's problem simultaneously, and this synergy could be optimised and taken into consideration in the expansion of the Power Potential concept. For this purpose, a set of commercial models and cases have been developed and analysed to evaluate the economics of the Power Potential bottom-up incremental approach against not-coordinated and fully the integrated (whole-system) approach and demonstrate the possible commercial synergies and conflicts due to the approaches taken to use DER services for both ESO and DSO.

Furthermore, a set of case studies has also been developed to demonstrate the implications of the corrective or preventive mode control strategy on the commercial synergies of reactive power services between distribution and transmission networks. In order to address this issue, a large-scale non-linear optimisation model has been developed, implementing state-of-the-art optimisation techniques with robust convergence properties.

As voltage control and reactive power requirement are local phenomena, it is critical for the ESO and DSO to be able to measure the market concentration of DER services to identify and prevent market power. A Herfindahl-Hirschmann (H) index is used as an indicator of market power. A set of case studies has been carried out to determine the H index for the system without and with Power Potential. The results provide evidence of the benefits of Power Potential. The increased number of participants facilitates more competition and reduces the market concentration in the provision of reactive power and voltage control services in the South-East part of the GB transmission system.

The key findings of our analysis are summarised in the following sections:

## Synergy and conflicts between DSO and ESO-based DER services

In general, there is a strong correlation between the operating conditions of transmission and distribution, e.g. undervoltage (or overvoltage) at transmission is propagated to distribution as well. Loads across the grid supply points (GSPs) and generators' output from PV or wind, given the proximity of the area, are correlated. This indicates that the same nature but different in magnitude voltage problems is likely to happen in both transmission and distribution; therefore, there is a likelihood of having synergy in using the DER services for both transmission and distribution. The synergy between the ESO and DSO occurs when the decisions to solve network problems at distribution also relieve network problems at transmission and vice versa, and this generally occurs when transmission and distribution experience the same problem.

However, in theory, there is a possibility of having different nature of voltage problems at different parts of the networks, e.g. some parts of the network which have a high penetration of DERs may experience overvoltage issue while the rest of the system which is heavily loaded experiences undervoltage issue. These conditions may trigger conflict between ESO and DSO if there is no coordination between them. In addition, an ESO centric solution, ignoring distribution network constraints, may violate distribution network constraints especially if the low-cost resources are connected to the constrained part of the distribution grid. Our studies also conclude that with no DSO-ESO coordination, the volume of reactive services needed to solve distribution and transmission problems tends to be higher which increases the associated cost.

In order to address this issue, a Distributed Energy Resources Management System (DERMS) is used in Power Potential to calculate the available DER capacity that can be used by the ESO taking into consideration local network constraints, which is the fundamental concept of Virtual Power Plant (VPP)[1,2]. Distribution network constraints will be solved first by the DSO before the remaining available DER capacity is offered to ESO as transmission services. Using this bottom-up incremental approach, the use of DER reactive services by ESO via DERMS will not violate distribution constraints in the Power Potential area. By implementing smart grid technologies in combination with DERMS control platform, the Power Potential incremental approach can be optimal (or close to) compared to the whole-system solution as discussed in the next section.

## Comparison between Power Potential's incremental versus whole-system approach

Table E. 1 compares the pros and cons of the two approaches, i.e. incremental and whole-system that have been identified during the study. The incremental approach taken by the Power Potential provides a balance between the complexity and accuracy in coordinating the use of DER services for

[1] A Virtual Power Plant is a flexible representation of a portfolio of DERs that can be used to make contracts in the wholesale market and to offer services to the system operator – subject to the firmness of access to distribution networks. A VPP not only aggregates the capacity of many diverse DERs, but it also creates a single operating profile from a composite of the parameters characterising each DER and incorporates spatial (i.e. network) constraints into its description of the capabilities of the portfolio.

[2] G. Strbac, D.Pudjianto, P.Djapic, "Market Framework for Distributed Energy Resources-based Network Services," a Power Potential report by Imperial College London, June 2018. https://www.nationalgrideso.com/document/118251/download

transmission while maintaining the integrity and security of the distribution system operation. It is essential to highlight that due to the adoption of the incremental approach, it is essential that the Power Potential framework considers measures to prevent the conflict. The use of the VPP concept, i.e. calculating the available resources that can be used by ESO considering local network constraints, can mitigate the conflict although it may not provide a maximum synergy that can be provided compared to the synergy produced by the integrated approach.

**Table E. 1 Comparison between incremental and whole-system (integrated) approach**

| Incremental approach | Whole-system (integrated) approach |
|---|---|
| Practical approach as the problems are decomposed to less complex problems and solved incrementally | More complex and computationally very intensive |
| It may be suboptimal, but the use of smart control[3] can provide "corrective" actions. DSO - ESO approach (Power-Potential concept) is very likely to perform better than ESO -DSO approach as the local distribution networks are more sensitive to DER outputs than the transmission network | Optimal from the system perspective but not necessarily optimal from ESO or DSO's individual perspective |
| It can trigger conflicts i.e.<br>- Active constraints in the other system (particularly ESO - DSO approach) or<br>- Access restriction to the DER capacity resources which incurs a higher cost to the other party | Maximise the synergy and access of DER capacity to both transmission and distribution services |
| The cost of using DER can be allocated more efficiently since the volume needed by each party is clearly identified. | Cost allocation between ESO and DSO requires decomposition of the benefits (more complex)[4] |

We have analysed the results of a range of characteristic case studies that have been performed to analyse and demonstrate the possible conflict and suboptimal synergy caused by the incremental approach. We conclude that the solution from DSO – ESO incremental coordination used by Power Potential will be close to the optimal solution from the integrated approach if the operation of the local distribution networks is optimised. This is because DERs will have a higher locational impact on local distribution compared to transmission; therefore, solving the distribution problem first is a

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3 The operation of the distribution network is optimised to reduce the overall cost.

4 It may require a more complex market mechanism as in the Power Potential project; see K.L.Anaya, M.G. Pollitt, "Reactive Power Management and Procurement Mechanisms: Lessons for the Power Potential Project," a report prepared for National Grid by Energy Policy Research Group University of Cambridge, June 2018.

pragmatic approach as indicated by the results of the case studies. This approach is also facilitated by the characteristics of the Power Potential distribution grid, which is relatively strong (“unconstrained”) in normal operating conditions. Another advantage of the Power Potential incremental approach is that the cost allocation of DER services to distribution and transmission can be tractable.

Our studies also demonstrate that the least-cost solution from DSO’s actions may not be the least-cost solution from the whole-system perspective. The whole-system coordination (integrated approach) will always produce the least-cost solution and maximise the synergy of using DER for both transmission and distribution. However, the cost allocation for the services to ESO and DSO cannot be directly determined as in the incremental approach. Appropriate regulatory framework and cost allocation or commercial mechanism should be developed in future to reward the DER services from ESO and DSO and also to incentivise DSO to facilitate access to DERs.

## Importance of DSO led smart control in distribution to maximise access for DER to ESO and the implications of preventive or corrective control modes on the ESO-DSO coordination

Most of the voltage control devices at transmission and distribution already operate in a corrective mode with automatic voltage regulators to maintain the voltage at the controlled node to be within a certain range. The same approach can be applied to Power Potential reactive services. In a preventive mode, DER will provide reactive power, either lagging or leading to maintaining the system voltages during intact and contingent conditions The preventive approach can ensure that when the contingency occurs, the voltages are kept within limits without any need for corrective actions from ESO.

In contrast, the corrective mode provides maximum controllability by enabling control devices to adapt to the actual real-time operating conditions. In this case, Power Potential requires participants to operate in voltage-droop control mode while DERMS offers dynamic voltage support by continuously adjusting the DER voltage set-points, and so already providing corrective control. This requires a sufficiently fast control system to adjust the settings of reactive sources and voltage control devices to respond to the system requirements in real time and the extent of the support would be limited by the speed of the control communication infrastructure. The pros and cons of implementing preventive and corrective control are summarised in Table E. 2. Table E. 2

**Table E. 2 Comparison between the characteristics of preventive and corrective modes**

| Preventive | Corrective |
|---|---|
| No need for immediate post-fault action | Need immediate action to restore security; Benefit from automation |
| No violation in operating limits | Operating limits may be temporarily violated |
| No time limit | Operating states of the system must be restored within a specific time limit, e.g. voltages at 400kV |

| | |
|---|---|
| | can be between +5% and +10% for 15 minutes[5]. |
| Risk of reducing access to DER capacity | Maximise access to the resources as the control settings are adaptive to network conditions |
| Higher cost | Lower cost |

Our analysis suggests that the preventive settings would need to be estimated carefully in order not to restrict the ESO access to DERs. A set of examples has been developed to demonstrate that a suboptimal preventive setting of transformers can limit the reactive capacity of DER that can be used by ESO. If this happens, ESO will need to use alternative options with a potentially higher cost to solve transmission voltage problems. Using the corrective control approach, DSO can maximise the availability of the DER's reactive capability for the ESO, as the settings are always optimised based on the real-time system condition.

## Impact of transmission outages on distribution constraints

The incremental approach assumes that the analysis of the transmission and distribution system can be carried out separately. The objective is to reduce the size and complexity of the system in question, which in turn will enable less time intensive analysis and computation. This approach is pragmatic considering the radial nature of the distribution network. Given that the Power Potential distribution systems, especially at 132 kV are interconnected via a tie-line, we have carried out a range of analysis to assess the impact of transmission system contingencies on the distribution and transmission system constraints in the Power Potential area in order to identify potential voltage and circuit-capacity constraints.

The key finding of the study is that the impact of transmission outages should be considered when calculating/aggregating the DER capacity that can be offered to ESO. The studies demonstrate that transmission outages, particularly, double circuit outages can exacerbate distribution network constraints which may reduce the capability of the Power Potential VPP[6]. A possible extension of the Power Potential concept is to use of DER services not only for supporting voltages but also for network flow management in distribution networks[7].

## Benefits of Power Potential in reducing market power in the provision of reactive power services

We have evaluated the benefit of the Power Potential in improving the competition in the reactive power market in the South East region. A Herfindahl-Hirschmann (H) index is used to measure the concentration of reactive power resources. Below 1000, the H index indicates that there is a sufficient number, similarly sized resources that can provide the services and hence, it is unlikely for

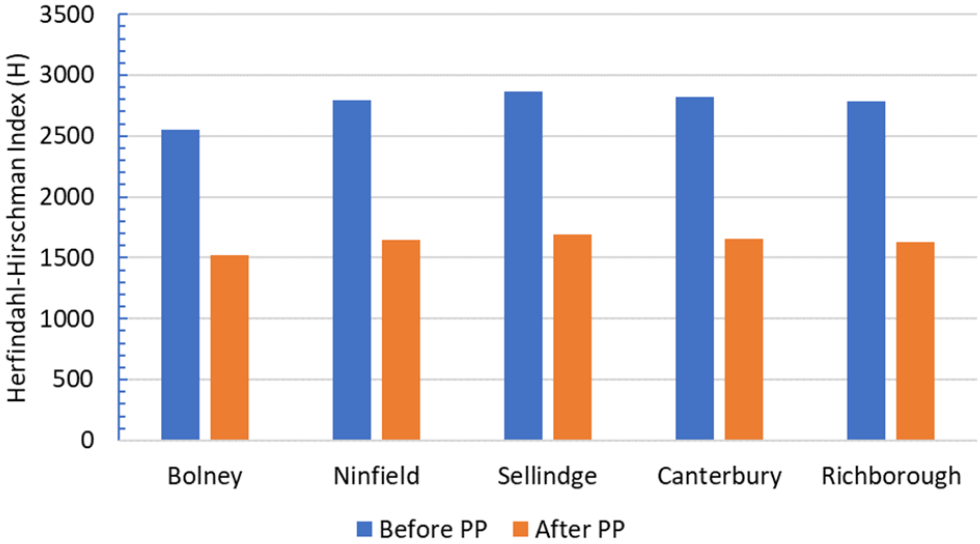
[5] Grid Code, ECC.6.1.4 Grid Voltage Variations

[6] Currently, the impact of transmission outages is not considered in DERMS.

[7] An active power service within the Power Potential framework uses DER to manage transmission thermal constraints and system balancing.

a market player to exercise market power. Between 1000 and 1800, the H index suggests that there is a mild concentration of resources which increases the risk of having market power. Beyond 1800, the resources are quite concentrated, and the likelihood of having a market power is high.

Figure E. 1 shows the H index for five GSPs (Bolney, Ninfield, Sellindge, Canterbury North, and Richborough), considering the locational aspect of reactive power and voltage control, for two different conditions, i.e. before the Power Potential and after the Power Potential project. It is shown that, before the Power Potential, reactive power resources at these locations are concentrated particularly to the large service providers and as the H index is greater 1800, it indicates that the number of participants is insufficient to facilitate competition in providing the reactive and voltage control services in these regions.




H<1000 : unconcentrated
1000 <H<1800 : moderately concentrated
H>1800 : highly concentrated

**Figure E. 1 H-index before and after Power Potential**

After the implementation of Power Potential, that enables small-scale DER to provide reactive support and voltage control services to the ESO, all the H indices fall below 1800 indicating significantly improved competition in the reactive power market. As it is expected that there will be more DERs participating in the Power Potential framework (and supplying reactive power and voltage control in the system) the H index will continue reducing.

The impact of DER market aggregation and system conditions on the market power index have also been analysed. It can be concluded that market aggregation of DER capacity can increase market power index as it brings more market power to the aggregated DER. The analysis also suggests that market power index also increases when the system is stressed or constrained to its operating limits. In distribution networks, the case of market power for providing reactive services tends to be stronger due to the local nature of reactive power and a relatively small number of service providers.

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# Acronyms

| | |
|---|---|
| DER | Distributed Energy Resource |
| DERMS | Distributed Energy Resources Management System |
| DG | Distributed Generation |
| DSO | Distribution System Operator |
| DSR | Demand Side Response |
| ESO | Electricity System Operator |
| GB | Great Britain |
| NETSO | National Electricity Transmission System Operator |
| PP | Power Potential |
| SCOPF | Security Constrained Optimal Power Flow |
| SVC | Static VAR Compensator |
| UK | United Kingdom |
| VPP | Virtual Power Plant |

# Chapter 1. Introduction

## 1.1 Context

Power Potential is a novel techno-economic framework designed to provide opportunities for distributed energy resources (DERs) to offer reactive power capability and voltage control services in the South East area of Great Britain's transmission system. In this region, demand for these services has increased in the past several years due to the rapid growth of DERs, new interconnection links, and reduced operating hours of large-scale conventional generation units as traditional sources. By enabling the provision of voltage control services by DERs, the need for investment in traditional transmission level reactive resources (e.g. Static VAR Compensators (SVCs), shunt capacitors/reactors) or engaging out-of-merit generation will be reduced, leading to lower costs to customers.

Although the current focus of the trial is to use DER reactive services to support transmission while respecting distribution network constraints, in principle, the Power Potential framework enables DERs to provide network services to support not only the Great Britain (GB) Electricity System Operator (ESO) but also to the local Distribution System Operator (DSO). DERs can provide an alternative lower-cost solution to the network reinforcement needed to solve network problems faced by both the GB ESO and the DSO. As DERs can serve both GB ESO and DSO, it is vital that the control and commercial frameworks used to allocate DER services for ESO and DSO do not trigger conflicts between the system operators. Instead, DERs can be used to solve the ESO and DSO problem simultaneously, and this synergy should be taken into consideration in the expansion of the Power Potential concept. For this purpose, a set of commercial models and cases have been developed and analysed to evaluate the economics of the Power Potential bottom-up incremental approach against the integrated (whole-system) approach and demonstrate the possible commercial synergies and conflicts due to the approaches taken to use DER services for both ESO and DSO.

The Distributed Energy Resources Management System[8] (DERMS) in Power Potential applies the Virtual Power Plant (VPP) concept where the DER resources are aggregated taking into consideration the local active network constraints in the system. A Virtual Power Plant is a flexible representation of a portfolio of DER that can be used to establish contracts in the wholesale market and to offer services to the system operator – subject to the firmness of access to distribution networks. This is illustrated in Figure 1.

[8] DERMS is the control platform used in the Power Potential project for DER commercial and technical dispatch.

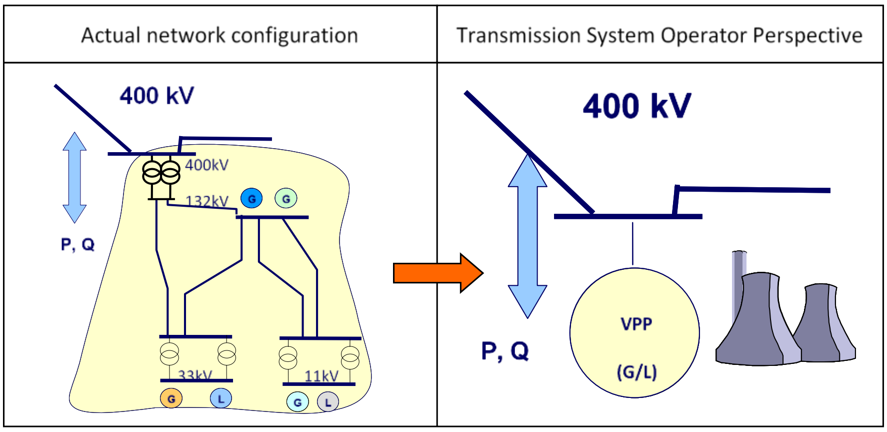


**Figure 1 Characterisation of DER as a Virtual Power Plant**

A VPP not only aggregates the capacity of many diverse DER, but it also creates a single operating profile from a composite of the parameters characterising each DER and incorporates spatial (i.e. network) constraints into its description of the capabilities of the portfolio. The VPP is characterised by a set of parameters usually associated with a traditional transmission connected generator, such as scheduled output, ramp rates, voltage regulation capability, reserve etc. In the context of providing reactive power support, the characteristics of the Power Potential VPP have been studied and analysed in our previous report[9].

Thus, when the ESO accept and make use of the offered capability from DERMS, the approach ensures that this will not trigger operating limit violation in the local distribution networks. However, it was not clear whether such an approach can lead to optimal results as produced by an integrated approach, which solves the whole-system optimisation problem at once. Therefore, this work investigates and analyses a range of cases to demonstrate the synergies or conflicts while using the incremental approach and compares with the cases where the allocation of resources is optimised in an integrated manner using the whole-system approach.

Furthermore, the use of DER reactive power services to support transmission voltage management is expected to be a novel approach to facilitate the competition of providing those services which are currently dominated by large-scale service providers.  However, the impact of enabling DER to participate in the reactive power market has not been analysed and understood fully and therefore, the objective of this work is to provide additional evidence regarding the benefits of the Power Potential framework in facilitating the competition in providing voltage control and reactive power services.

## 1.2 Key objectives

The specific objectives of this work can be summarised as follows:

- To develop modelling for assessing synergies and conflicts between ESO and DSO commercial objectives to identify the conditions where there may be potential synergies and conflicts of

[9] G. Strbac, D.Pudjianto, , P.Djapic, "Market Framework for Distributed Energy Resources-based Network Services," a Power Potential report by Imperial College London, June 2018. https://www.nationalgrideso.com/document/118251/download

using DER for supporting transmission and local distribution networks. The model will evaluate a commercial framework that would allow the allocation of DER services for DSO or ESO or both, through some characteristic cases.

- To evaluate the performance of the incremental and the whole-system based commercial framework. Using some characteristic cases, we analyse the economic performance of adopting a sequential approach to allocating services in which the DER resources are first allocated to solve the distribution network problem and then, additional resources are allocated to accommodate the ESO's requirements. This approach is compared with the whole-system concept, where the resources are allocated to solve both transmission and distribution systems simultaneously at the minimum costs.

- To analyse the impact of preventive and corrective control. The use of preventive mode may reduce the need for responding rapidly to unplanned events (changes in generation or demand, or outages) but at the same time, it may limit the use of system resources. On the other hand, the corrective mode will allow the system to adapt and to be optimised following the changes in the system conditions; however, this may incur the additional cost associated with the control and communication infrastructure and operation.

- To carry out market power assessment by performing a range of case studies and sensitivity analysis to demonstrate the conditions where specific resources may have market power due to their locations and their technical properties. The level of market power will be determined by the adopted Herfindahl-Hirschmann (H) index.

- To derive the lesson learnt and the main findings from the range of analysis carried out in this work.

# Chapter 2. Synergies and conflicts between DSO and ESO-based DER services

## 2.1 Context

Full coordination between ESO and DSO in using DER services would minimise the overall operating cost; it is however technically very challenging to carry out fully coordinated control between the local district and national electricity network infrastructure particularly in the decentralised system where the operating responsibility of the system is decomposed to different commercial entities, i.e. ESO is responsible for transmission and DSO for the distribution system.

The synergy between the ESO and DSO occurs if the decisions to solve network problems at distribution also relieve network problems at transmission and vice versa. This can be guaranteed if the distribution and transmission problems are solved simultaneously using an integrated approach to minimise cost. In contrast, the conflict between the ESO and DSO operating/market decisions occurs if decisions to solve network problems at distribution trigger/aggravate network problems at transmission and vice versa. This is likely to occur when the low-cost resources are located in weak[10] distribution areas, and distribution and transmission network problems are solved in an uncoordinated manner.

Voltage problems in distribution and transmission networks are generally driven by the same operating conditions. Undervoltage problems are typically experienced when high demand conditions coincide with low production of DER. In contrast, overvoltage problems generally occur when low demand conditions coincide with high DER output. Interconnectors connected at transmission will also have an impact on transmission, and at a certain extent, the impact may also be propagated to the distribution network. This effect may be relatively insignificant, and it can be managed by the automatically adjusting on-load tap changers in supergrid and primary substations. Exporting power via interconnectors during high demand conditions will aggravate the undervoltage conditions. On the other hand, importing power via interconnectors during these demand conditions will reduce voltage problems. The opposite occurs when the system demand is low.

In general, there is a strong correlation between the operating conditions of transmission and distribution, e.g. undervoltage (or overvoltage) at transmission is propagated to distribution as well. Loads across the grid supply points (GSPs) and generators' output from PV or wind, given the proximity of the area, are correlated. This indicates that the same nature of voltage problems is likely to occur in both transmission and distribution; therefore, there is a likelihood of having synergy in using the DER services for both transmission and distribution. The synergy between the ESO and DSO occurs when the decisions to solve network problems at distribution also relieve network problems

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at transmission and vice versa, and this generally occurs when transmission and distribution experience the same problem.

However, in theory, there is a possibility of having different nature of voltage problems at different parts of the networks, e.g. some parts of the network which have a high penetration of DER may experience overvoltage issue while the rest of the system which is heavily loaded experience undervoltage issue. These conditions may trigger conflict between ESO and DSO if there is no coordination between them. In addition, an ESO centric solution, ignoring distribution network constraints, may violate distribution network constraints especially if the low-cost resources are connected to the weak part of the distribution grid.

## 2.2 Potential conflicts due to lack of DSO-ESO coordination

We have identified and investigated characteristic cases where the conflicts between ESO and DSO interests may occur when using DER. In this context, two main types of conflicts analysed are:

1. Decisions taken by one operator trigger or violate network constraints in the jurisdiction of other system operators;
2. Decisions taken by DSO limit the capacity of DER that can be accessed and utilised by ESO leading to a higher cost solution for the ESO.

The first type of conflict is demonstrated in this section through some characteristic examples while the second type will be discussed in the next chapter when we analyse the importance of DSO-led smart control.

### 2.2.1 An illustrative case on a simple system

Figure 2 illustrates a simplified distribution network with two DERs, i.e. $G_A$ and $G_B$ which offer reactive services at £2/Mvar and £3/Mvar respectively. The transmission network requires +40 Mvar support[11] from DER to solve its undervoltage problems (not explicitly shown). There is no operating limit violation at distribution before DER provides reactive services to transmission. In this illustrative analysis, it is assumed that the allowed voltage fluctuations are ±5% from the nominal value.

[11] As a convention +Mvar by a DER means reactive injection and -Mvar means reactive power absorbed by DERs.

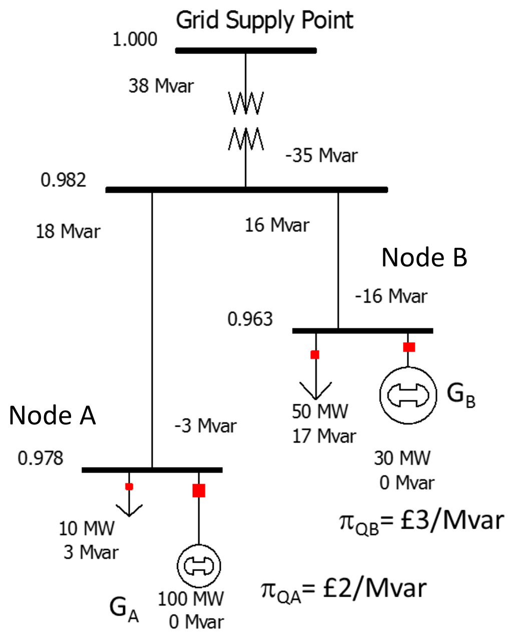



**Figure 2 A distribution system with DER**

Without the DSO-ESO coordination, ESO will procure the +40 Mvar reactive services from $G_A$ since the price of reactive services from $G_A$ is lower than the prices offered by $G_B$. The cost of the services from $G_A$ is £80. However, the +40 Mvar injection from $G_A$ will increase the voltage at node A to 1.077 p.u. (7% above its nominal voltage while the limit is 5%). The ESO decision then creates a conflict as it triggers an active constraint in the system. This is illustrated in Figure 3.

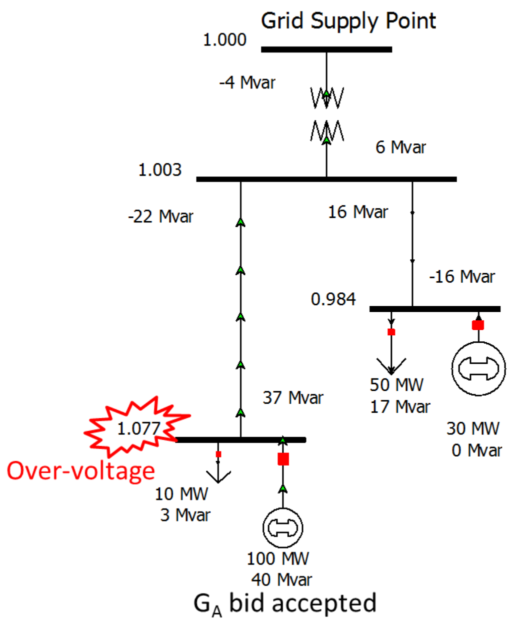



**Figure 3 An overvoltage problem caused by no ESO-DSO coordination**

In the context of Power Potential, the DSO-ESO incremental approach prevents such conflict from occurring since the VPP aggregation has considered local network constraints when calculating the available DER capacity that can be used by ESO. In this case, the solution will be to use +25 Mvar from $G_A$ and +15 Mvar from $G_B$. The voltage at node A reaches the upper limit indicating that the solution already uses the most economical source, i.e. $G_A$ before using $G_B$. This solution is also the same as the solution obtained by the integrated approach.

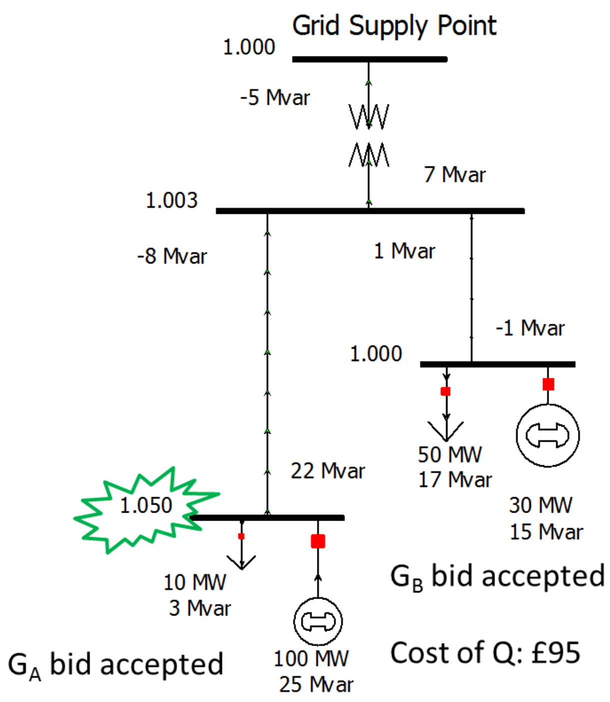



**Figure 4 A solution from the Power Potential approach**

It is interesting to note that the cost of the solution increases to £95. This indicates that the operating constraints at distribution may increase the cost for transmission since the constraints restrict the access to the lower cost resources needed by transmission.

### 2.2.2 An illustrative case on the Power Potential system

A different case study has been developed on the Power Potential test system to demonstrate the potential conflict between ESO and DSO if there is lack of coordination and commercial decisions associated with the use of DER reactive power services. For the purpose of this case study, the summer minimum demand condition coinciding with high DER output and high import (2GW from IFA and 330 MW from NEMO) is considered. Moreover, the assumption is made that the generating units at Dungeness are not operating and hence cannot provide voltage control and reactive power services. This condition leads to high voltages across the system and an overvoltage problem at Ninfield 400kV node as illustrated in Figure 5.

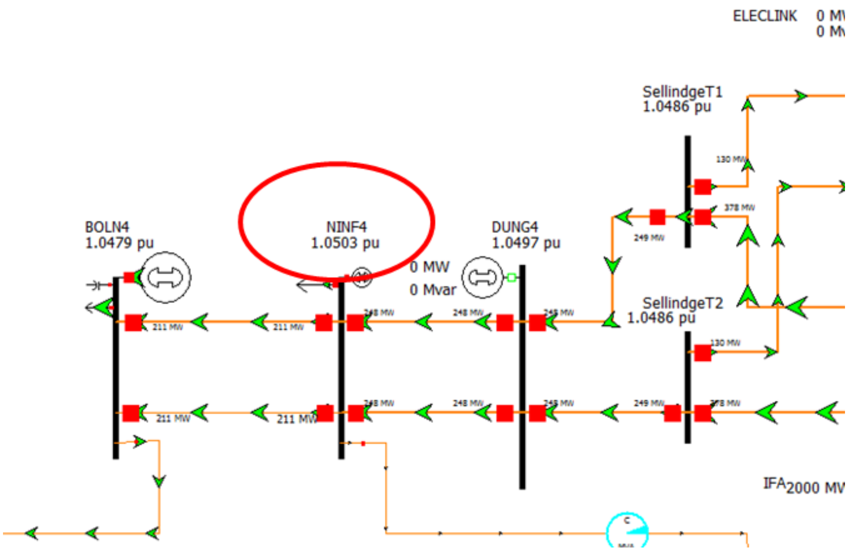



**Figure 5 An overvoltage problem at the transmission**

At the same time, there is a transformer circuit outage in the Ninfield distribution area (the detail of the location is omitted) and the voltage at the node where the Power Potential unit is at 0.95 p.u as illustrated in Figure 6. The operating voltages across the distribution network are still within the operating limits.

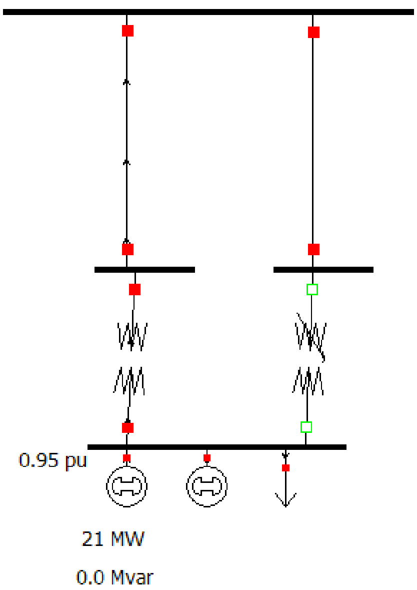



**Figure 6 A transformer circuit outage in Ninfield distribution area**

Without DSO-ESO coordination, ESO may choose to procure -9 Mvar reactive services from the Power Potential unit shown in Figure 6. While these services bring the voltage at the Ninfield 400kV node back to be below 5%, this action triggers an undervoltage problem at the local distribution where the Power Potential unit delivering the service is connected to. The voltage drops to 0.92 p.u. due to increased reactive absorption by the respective Power Potential unit. This case is illustrated in Figure 7.

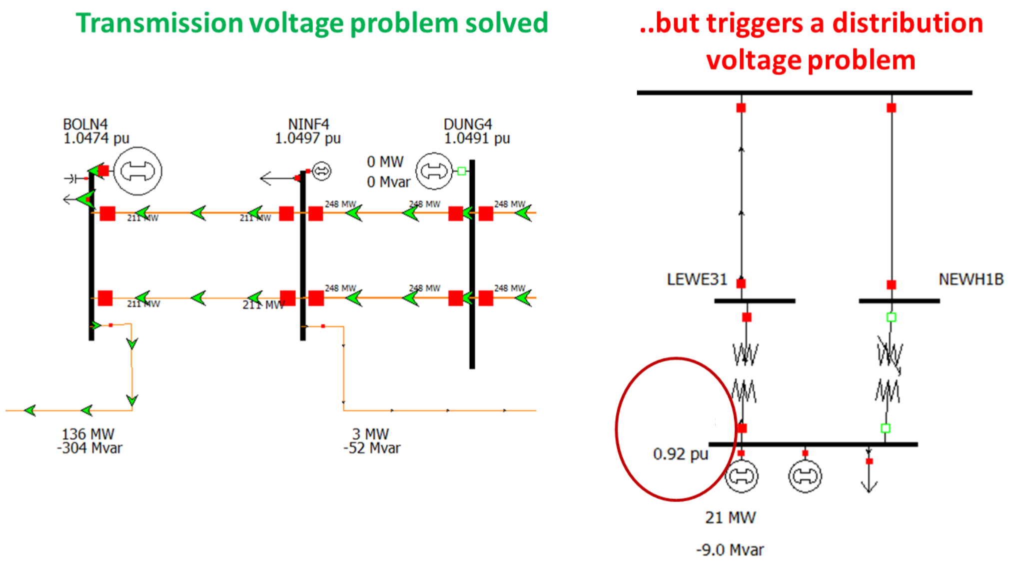



**Figure 7 An undervoltage problem caused by non-coordinated DSO-ESO control actions**

In the context of Power Potential, the maximum volume that can be used from the Power Potential unit in Figure 6 is -3 Mvar; therefore, the Ninfield VPP will get -6 Mvar from other Power Potential unit and ensures that the reactive dispatch does not violate the distribution network operating constraints. This case is illustrated in Figure 8.

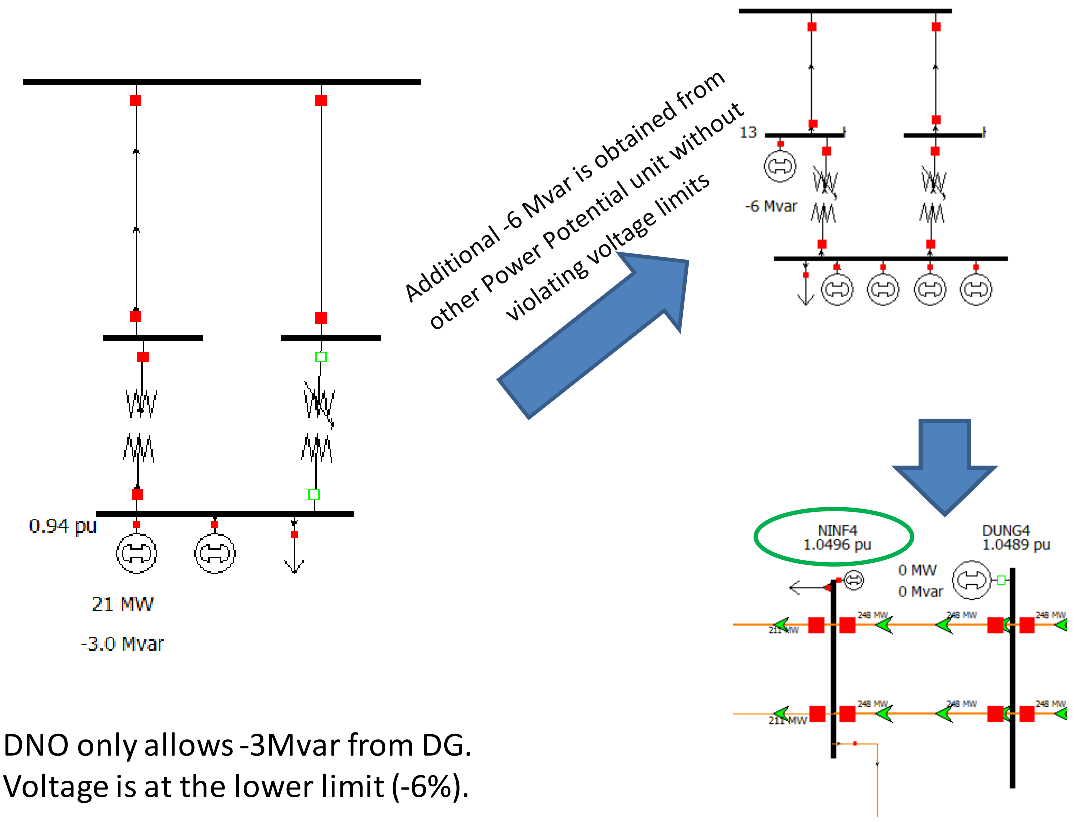



**Figure 8 A solution from the Power Potential approach**

Through these characteristic examples, we demonstrate the importance of DSO-ESO coordination in order to mitigate the conflicts between the ESO and DSO.

## 2.3 Comparison between three core cases: no ESO-DSO coordination, incremental coordination, and whole-system coordination

### 2.3.1 No ESO-DSO coordination

No coordination between ESO and DSO does not always trigger a conflict but the volume or the allocation of DER used to solve transmission and distribution problems is likely to be sub-optimal leading to a higher cost solution. This is demonstrated by the following example.

Figure 9 illustrates a simple distribution system with operating voltage limits of ±5%. The voltage at bus A (where $G_A$ is connected) is below the operating limit. There are two generators: $G_A$ and $G_B$. The price of reactive power service from $G_A$ and $G_B$ is £3/Mvar and £2/Mvar. At this point, distribution imports +31 Mvar from the transmission. At the same time, transmission requires DER to inject +20 Mvar to the distribution to reduce the import from the transmission.

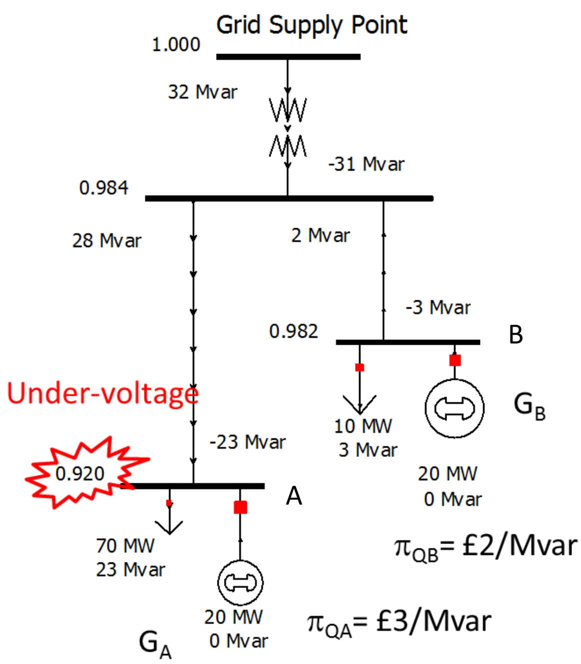



**Figure 9 An illustrative case: no ESO-DSO coordination**

From the DSO perspective, to solve the undervoltage problem at bus A, DSO will accept +11 Mvar bid from $G_A$. This will increase the voltage at bus A to 0.95 p.u. which is just at the lower limit. In this case, +11 Mvar is the minimum amount needed to be procured to maintain the voltage within limits. The cost of purchasing this service is £33. DSO does not purchase reactive power service from $G_B$ although the price is lower because it will require more than +30 Mvar from $G_B$ to increase the voltage at bus A; this will cost more than £60. This DSO-based solution is illustrated in Figure 10.

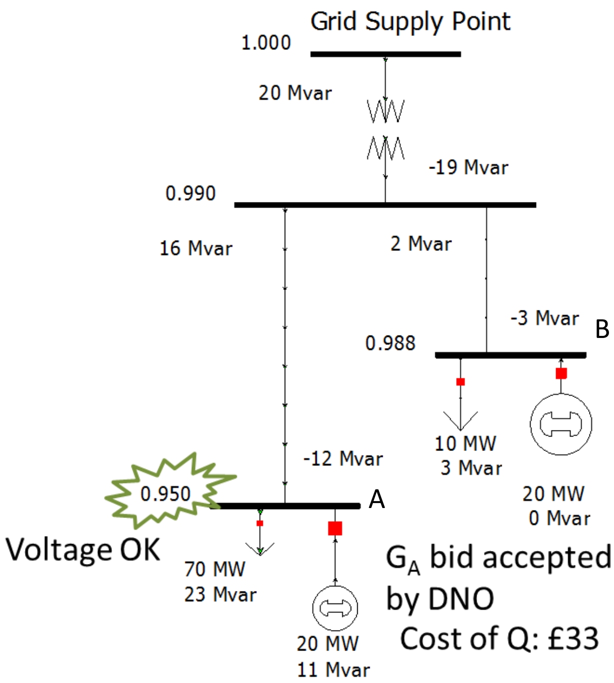



Figure 10 DSO solution for the undervoltage problem at the distribution

From the transmission perspective, the least-cost solution is to accept +20 Mvar bid from $G_B$ since $\pi_B < \pi_A$. The cost of this service is £40. As shown in Figure 11, the reactive injection from $G_B$ actually improves the voltage at bus A from 0.92 p.u to 0.931 p.u. However, additional Var is still required to bring back the voltage at bus A to be within its operating limit.

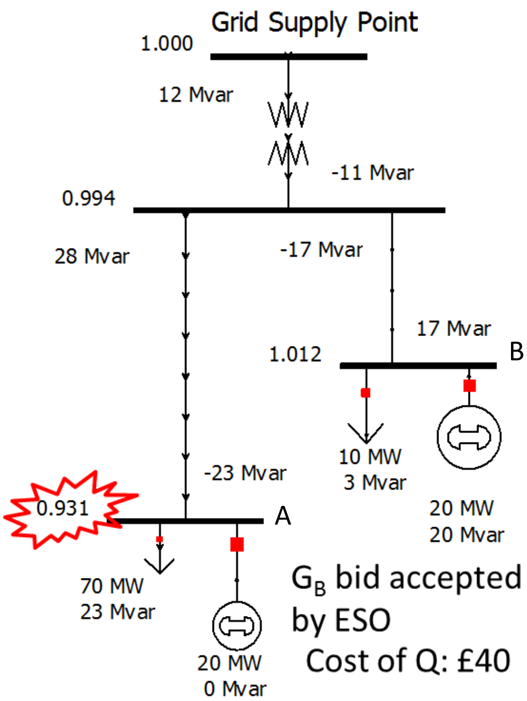



Figure 11 ESO solution to get the least-cost reactive source

If the bids accepted by DSO and ESO are made separately without any coordination and no exchange information between DSO and ESO, then the cost of the solution is £73 (i.e. £33 for service to DSO and £40 for the service to ESO).

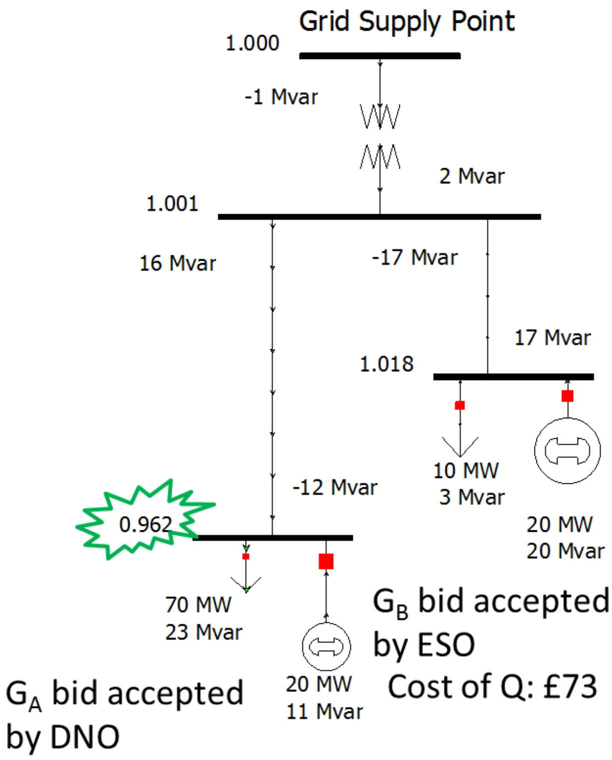



**Figure 12 ESO-DSO's no coordinated solution**

### 2.3.2 Incremental approach: DSO – ESO

We compare the solution obtained by "No-Coordinated Solution" discussed in section 2.3.1, with the coordinated solution using an incremental approach where the DSO takes the first decision on how to use DER to solve the distribution problem followed by ESO decision to use the remaining DER capacity in the system to solve the transmission problem. This process should resemble the Power Potential approach, although the use of DER services for solving distribution network problems is not currently in the scope of the project (i.e. Power Potential does not solve distribution network problems, but it will not create one while delivering transmission services). The process is illustrated below.

Using the VPP approach, the DSO will use DER first to solve its local network issues. In this case, DSO will accept +11 Mvar reactive services from $G_A$ to restore the voltage at node A to 0.95 p.u as illustrated in Figure 13. Then, DSO will offer the remaining DER capacity to ESO.

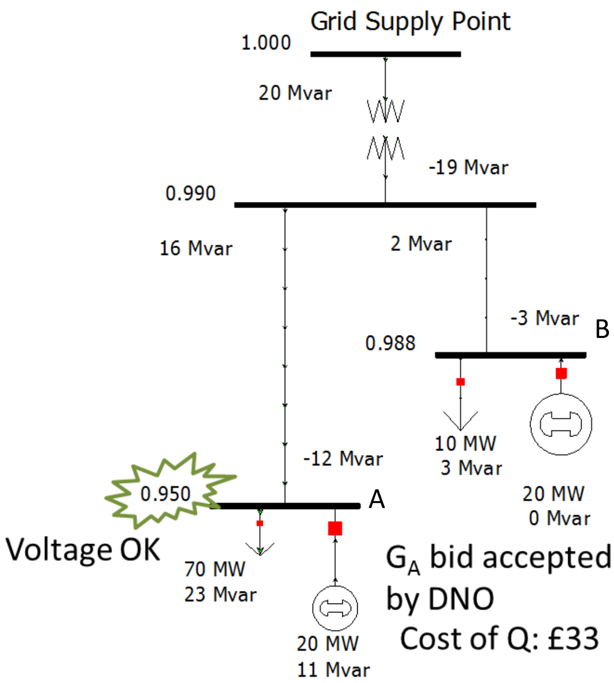



**Figure 13 Step 1 of DSO-ESO incremental approach: DSO solution for the undervoltage problem at the distribution**

It is essential to highlight that the decision by DSO is aligned with the objective of ESO and therefore, ESO only requires an additional +9 Mvar from $G_B$ to meet its requirement. $G_B$ is selected because the cost of its service is lower than the cost of reactive services from $G_A$. The total cost of reactive service is then £51. By having +9 Mvar injection at node B, the voltage at bus A is slightly improved and increases to 0.956 p.u. The state of the system with the solution is shown in Figure 14.

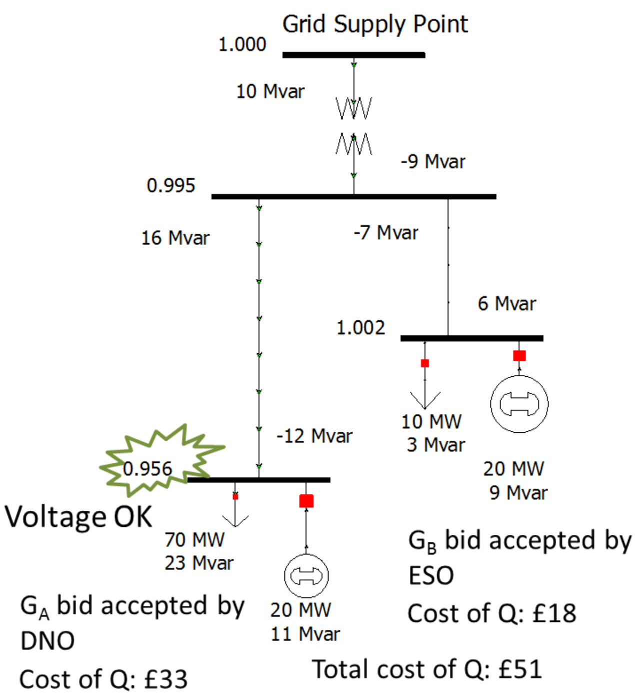



**Figure 14 Step 2 of DSO-ESO incremental approach: ESO uses the DSO solution and adds more reactive supports to meet its requirement**

This example demonstrates that the information related to DSO procurement of DER services will need to be provided to the trading platform, that would then reduce the additional reactive services need to be contracted by the ESO to meet their system requirements at minimum additional costs.

### 2.3.3 Integrated (whole-system) approach

As indicated by the previous sections, there is room to improve the synergy of the solutions taken by the DSO and ESO. In this case, using the whole-system model, we analyse the optimal solution through coordinating transmission and distribution requirements. The solution from the integrated approach is different compared to other previous approaches. In this case, +8 Mvar is required from $G_A$, and +12 Mvar is required from $G_B$. The voltage at node A is at the lower operating limit indicating that the amount of reactive support purchased to restore the voltage is minimum. The total cost of all reactive services from $G_A$ and $G_B$ is £48. This is lower than the costs in previous approaches.

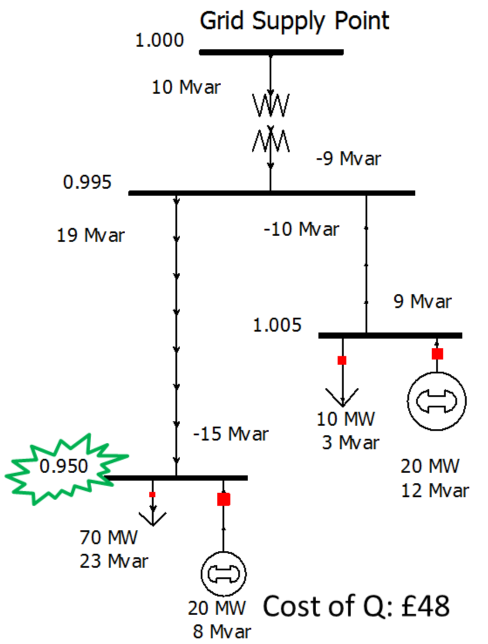



Figure 15 Integrated (whole-system) solution

In contrast to other approaches, where the allocation of reactive power services to support DSO and ESO is tractable which helps the cost allocation of the services, using the integrated approach, that information is not directly available. While outside the scope of this work, it is worth to highlight that such cost allocation methods will need to be developed in future shall the integrated approach be deployed in the system.

### 2.3.4 Comparison across different approaches

Table 1 summarises the volume of reactive power services and the associated cost of the services from $G_A$ and $G_B$ across different scenarios. The results demonstrate that the cost of a non-coordinated solution is the highest while the whole-system coordination (integrated approach) produces the least-cost solution. The solution from the DSO-ESO incremental approach is relatively close to the optimal solution (integrated approach).

**Table 1 Volume and cost of reactive power services in different scenarios**

| | Mvar | | Cost (£) | | |
|---|---|---|---|---|---|
| | $G_A$ | $G_B$ | $G_A$ | $G_B$ | Total |
| Non-coordinated | +11 | +20 | 33 | 40 | 73 |
| Incremental coordination: DSO - ESO | +11 | +9 | 33 | 18 | 51 |
| Whole-system coordination (integrated) | +8 | +12 | 24 | 24 | 48 |

While the study was carried out on a simple system, there are few general conclusions that can be derived from this exercise, i.e.:

- Non-coordinated solutions may cause constraint violation (as there may be conflicts between DSO and ESO requirements) and over procurement of DER services that would tend to increase the cost of services substantially.
- The DSO – ESO incremental coordination will be feasible and tend to be similar to the solution from the integrated approach since DERs will have a higher locational impact on local distribution compared to transmission; therefore, Power Potential concept is reasonable as solving the distribution problem first is a rational approach, as indicated by the results of the case studies, although the least-cost solution from individual system operator's actions may not be the least-cost solution from the whole-system perspective.
- The whole-system coordination (integrated approach) will always produce the least-cost solution and maximise the synergy of using DERs for both transmission and distribution; however, the cost allocation for the services to ESO and DSO would be more complex when compared with the incremental approach.

## 2.4 The synergy of using DERs on the Power Potential system: illustrative cases

A set of case studies has been developed on the real Power Potential system to demonstrate the need for optimal DSO-ESO coordination. For the purpose of this study, a summer minimum demand with high DER output and high import (IFA: 2GW and NEMO 330 MW) is used. The low demand condition coincides with high import, and high DER output leads to high voltages across the system under investigation. Due to this condition, there is overvoltage at 400kV Ninfield node as shown in Figure 16.

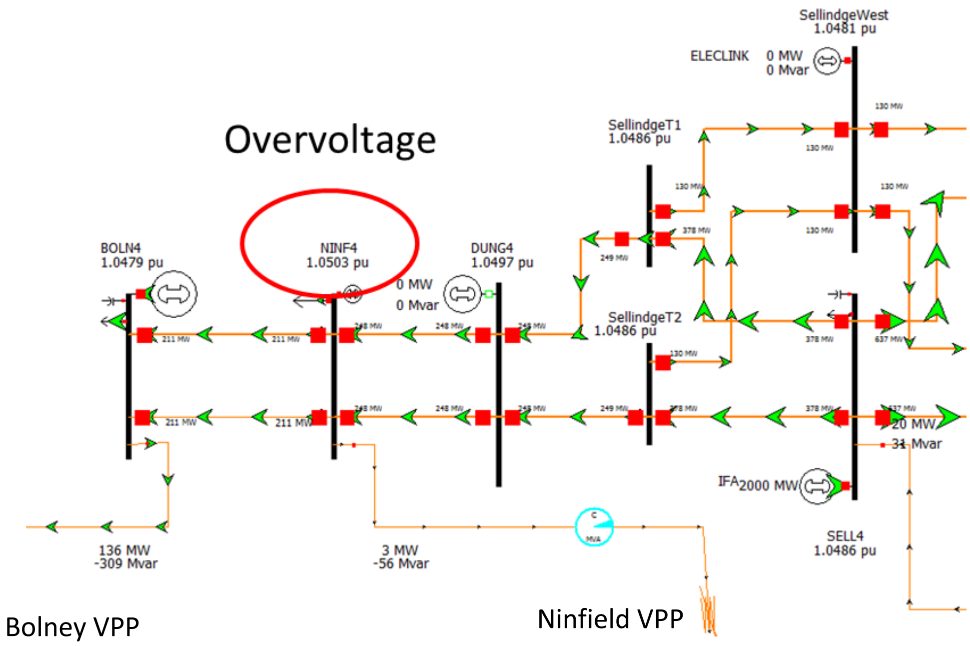



Figure 16 Overvoltage at Ninfield 400kV

In order to reduce the voltage, a Power Potential unit in Ninfield VPP is instructed to absorb -9 Mvar as shown in Figure 17. The location and the name of busbars and generators are purposely omitted.

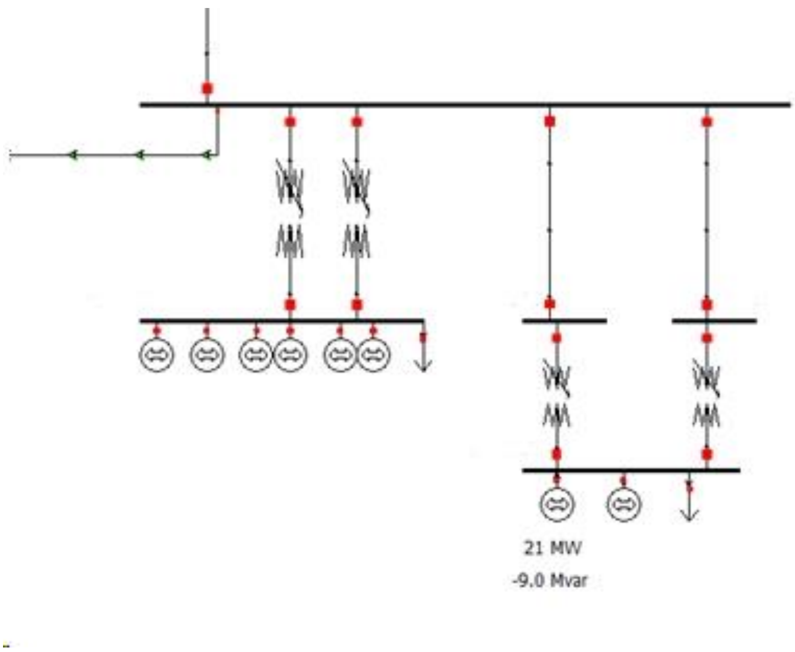



Figure 17 A power Potential unit in Ninfield VPP is used to correct the overvoltage problem at Ninfield 400 kV

By increasing the reactive load at Ninfield, the overvoltage problem can be solved as shown in Figure 18. The voltage at 400 kV Ninfield node is reduced back below +5% of its nominal voltage. It also improves the voltage profiles slightly across the system.

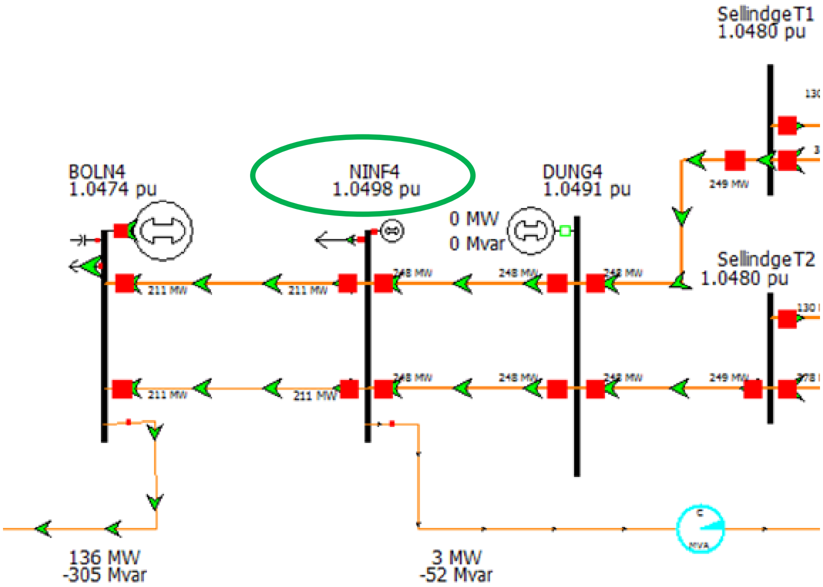



**Figure 18 A power Potential unit in Ninfield VPP is used to correct the overvoltage problem at Ninfield 400 kV**

In order to demonstrate the importance of synergy between ESO and DSO, we have developed a case where an overvoltage problem also occurs at the local distribution network where the selected Power Potential generating unit is required to absorb Var. One of the transformers is out of service which drives an overvoltage (7% above its nominal voltage) at the respective node as illustrated in Figure 19.

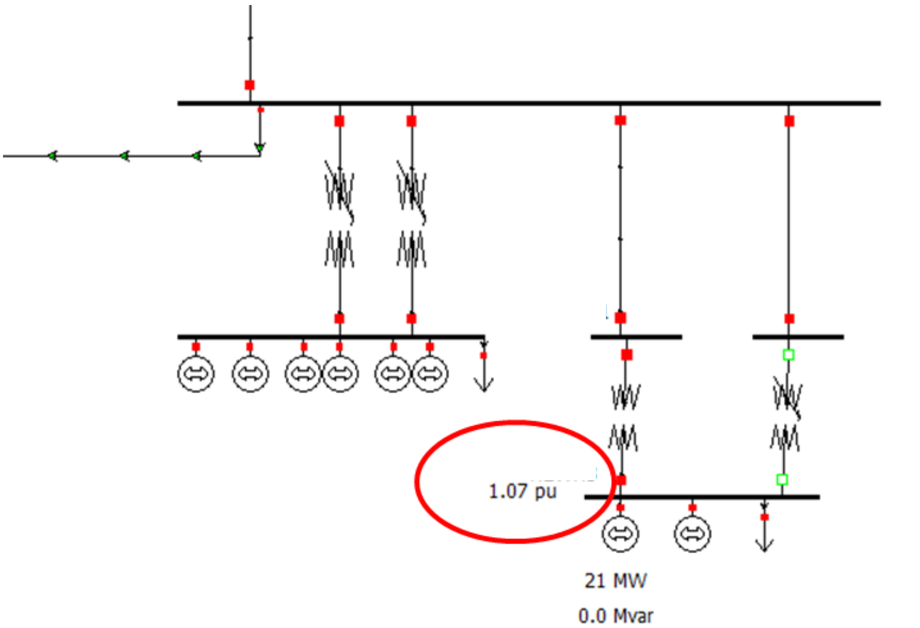



**Figure 19 A local overvoltage problem at Ninfield**

It is important to note that ESO can use -9 Mvar from another Power Potential unit connected to a different node in Ninfield GSP (assuming the prices for the reactive services are the same) to solve the problem at the 400 kV Ninfield. However, this will not solve the overvoltage at the local distribution network mentioned previously. In order to solve the local voltage problem, the DSO will require -3 Mvar from the local Power Potential generator to bring the voltage at the local 33 kV node in Ninfield to be within the limit ( ±6%). The total volume of reactive support needed is -12 Mvar; but if the ESO uses the same local Power Potential generator, the total volume of reactive power needed is -9 Mvar since the same service solves both overvoltage at local and transmission network simultaneously.

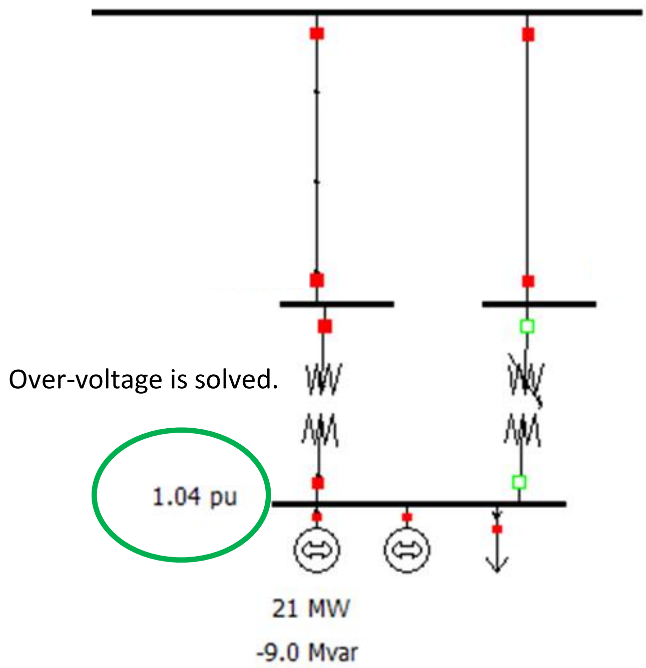



**Figure 20 Synergy of using a Power Potential unit to solve the overvoltage at the transmission and the local distribution grid**

In the context of DSO-ESO incremental approach, the approach is to use -3Mvar by DSO to solve the local overvoltage problem, and the ESO can use -6 Mvar from the same unit or other units (if the price is lower) to solve the overvoltage at the transmission system. In this case, there is a synergy of using the same resource (i.e., -3 Mvar) to solve both transmission and distribution problems; while the additional -6 Mvar is used mainly to solve the transmission problem. Without coordination, the volume and consequently the cost of reactive services needed to solve transmission and distribution problems will be higher.

## 2.5 Comparison between the Power Potential's incremental versus whole-system approach

Based on the range of analyses that have been carried out, we analyse and compare the pros and cons of the two approaches, i.e. incremental and whole-system (integrated), that have been identified during the study. The incremental approach taken by the Power Potential provides a balance between the complexity and accuracy in coordinating the use of DER services for transmission while maintaining the integrity and security of the distribution system operation. It is important to highlight that due to the adoption of the incremental approach, it is critical for the

Power Potential framework to consider measures to prevent the conflict. The use of the Virtual Power Plant concept, i.e. calculating the available resources that can be used by ESO taking into account local network constraints, can mitigate the conflict although it may not provide a maximum synergy that can be provided compared to the synergy produced by the integrated approach. The pros and cons of the incremental and whole-system (integrated) approach are summarised in Table 2.

**Table 2 Comparison between incremental and whole-system (integrated) approach**

| **Incremental approach** | **Whole-system (incremental) approach** |
|---|---|
| Practical approach as the problems are decomposed to less complex problems and solved incrementally | More complex and computationally intensive |
| Maybe suboptimal but the use of smart control[12] can provide "corrective" actions. DSO-ESO approach is likely to perform better than ESO-DSO approach as distribution is more sensitive to DER than the transmission | Optimal from the system perspective but not necessarily optimal from ESO or DSO's individual perspective |
| It may trigger conflicts i.e.<br>- Active constraints in the other system (particularly ESO-DSO approach) or<br>- Access restriction to the DER capacity resources which incurs a higher cost to the other party | Maximise the synergy and access of DER capacity to both transmission and distribution services |
| The cost of using DERs can be allocated more efficiently since the volume needed by each party is clearly identified. | Cost allocation between ESO and DSO requires decomposition of the benefits (more complex) [13] |

We have analysed the results of a range of characteristic case studies that have been performed to analyse and demonstrate the possible conflict and suboptimal synergy caused by the incremental approach. We conclude that the solution from DSO – ESO incremental coordination used by Power Potential will be close to the optimal solution from the integrated approach if the operation of the local distribution networks is optimised. DERs will have a higher locational impact on local distribution compared to transmission; therefore, solving the distribution problem first tends to be a reasonable approach as indicated by the results of the case studies. This approach is also facilitated by the characteristics of the Power Potential distribution grid, which is relatively strong

[12] The operation of the distribution network is optimised to reduce the overall cost.

[13] It may require a more complex market mechanism as in the Power Potential project; see K.L.Anaya, M.G. Pollitt, "Reactive Power Management and Procurement Mechanisms: Lessons for the Power Potential Project," a report prepared for National Grid by Energy Policy Research Group University of Cambridge, June 2018.

(“unconstrained”), particularly under normal operating conditions. Another advantage of the Power Potential incremental approach is that the cost allocation of DER services to distribution and transmission can be tractable.

However, it is important to note that the least-cost solution from DSO’s actions may not be the least-cost solution from the whole-system perspective. The whole-system coordination (integrated approach) will always produce the least-cost solution and maximise the synergy of using DERs for both transmission and distribution; however, the complexity of the modelling would increase the order of magnitude and also the cost allocation process (between DSO and ESO) is more complicated when compared with the incremental approach.

# Chapter 3. Role and value of DSO-led smart control

In the previous work, we demonstrated that the role of DSO was critical in aggregating and enabling access and control to DERs to provide reactive power services. DSO should optimise the access to DERs not only to minimise the DSO cost but also the cost of the whole system, including the ESO cost. In this context, the DSO should optimise the access to DERs for the ESO. Currently, there is no framework for that, and also, the DSO is not incentivised to have such a role.

In Power Potential, the capacity of the DERs that can be offered to the ESO, while taking into account network constraints, should be optimised and not unnecessarily be constrained by the DSO's operating strategies. In this context, we analyse the use of preventive and corrective control on the ability of the distribution system to optimise the access to DERs and develop some cases through a set of characteristic examples using a simple test system and the Power Potential network to demonstrate the importance of distribution network optimisation using smart control (e.g. optimisation of tapchanging transformers, reactive compensations, etc.) which enables flexibility and optimal access to DER capacity.

## 3.1 An illustrative case on a simple system

A simple distribution system model (Figure 21) is used for this study. The problems are twofold: (i) some distribution voltages are below the operating limit (i.e. 5%) and (ii) the transmission grid wants the reactive import is reduced to 4 Mvar (currently is 25 Mvar). DSO has several options to restore the voltages back to be within the statutory limit. There are two generating units ($G_A$ and $G_B$) that can provide reactive services and a tap changing transformer to control voltages.

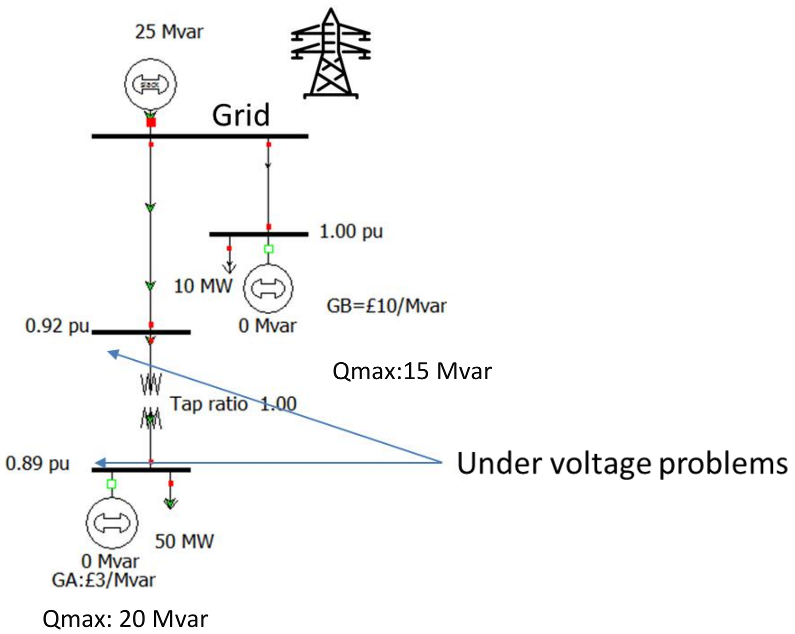



Figure 21 A simple distribution system with undervoltage problems

### 3.1.1 Non-smart (preventive) mode

The optimal decision for the DSO is to change the tap ratio to improve the voltage at the end of the feeder and to procure reactive services from $G_A$ by +4 Mvar to maintain all voltages between ±5% operating limits. The cost of the services is £12. The new state of the system after the implementation of the solution is shown in Figure 22.

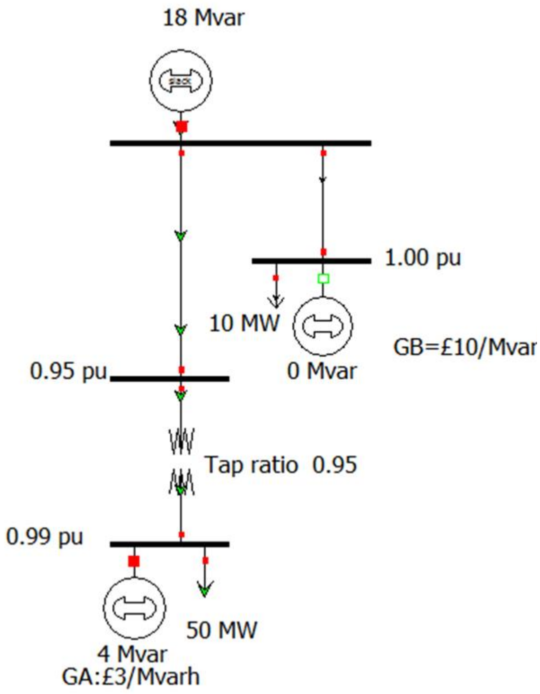



Figure 22 The state of the distribution system after the implementation of the DSO's solution

Based on the incremental approach, DSO offers the remaining capacity subject to network constraint to the ESO. Assuming the tap setting is operated in a preventive mode according to the DSO's system optimisation as shown in Figure 22, the aggregated remaining capacity, subject to the local network constraints, that can be offered to the ESO is as follows:

- $G_A$: additional +7 Mvar at £3/Mvar
- $G_B$: all capacity (+15 Mvar) at £10/Mvar

Based on this information, ESO will purchase +7 Mvar capacity from $G_A$ and 6 Mvar from $G_B$. The total reactive services from $G_A$ and $G_B$ is +17 Mvar (including +4 Mvar reactive services to DSO). Reactive import from transmission reduces by +21 Mvar as by providing local reactive services, it reduces 4 Mvar reactive losses in the distribution system. The additional Var procured by ESO will cost £81 (+7 Mvar@£3/Mvar + 6 Mvar@£10/Mvar), and the total cost of services including the cost of service to DSO is £93.

It is important to highlight that the maximum reactive injection from $G_A$ is +11 Mvar although the maximum reactive capability of $G_A$ is +20 Mvar since the local voltage is already at the upper limit, i.e. 1.05 p.u. This is illustrated in Figure 23.

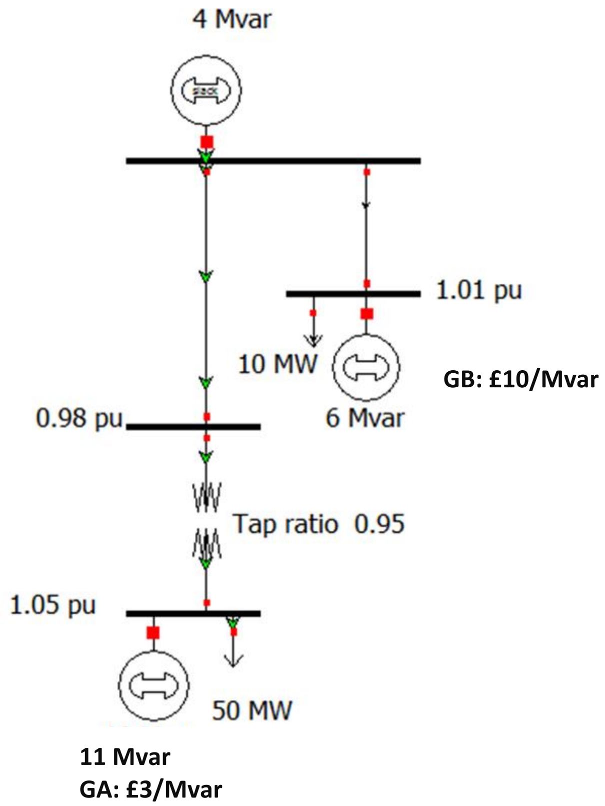



**Figure 23 DSO-ESO incremental approach solution with preventive mode**

However, if the problems are solved in an integrated manner, the solution will use +16 Mvar from $G_A$ to solve the local distribution and transmission problems concurrently. In order to use +16 Mvar from $G_A$, the setting of the tap position is not changed from the nominal position (1 p.u.). This contrasts with the DSO-centric solution since by changing the setting of the tapchanging transformer to 0.95 p.u., DSO can minimise the purchase of reactive services from $G_A$. However, the new tap setting will constrain the ESO access to $G_A$, and the ESO will need to purchase more expensive reactive services from $G_B$. The cost of the integrated solution is £48 (compared with £93 from the incremental DSO-ESO approach).

From this study, we learn that DSO should have a role in facilitating ESO to access DER capacity in order to minimise the overall system cost; however, this may lead to an increase in the operating cost of the DSO. However, in contrast to the tractable cost allocation in the incremental approach, it is not yet clear how the cost of DER services should be allocated to DSO and ESO in this case. Therefore, appropriate regulatory framework and cost allocation or commercial mechanism should be developed in future to incentivise DSO to carry out such an important role. The comparison between the incremental and integrated solution with non-smart control (or preventive mode) is illustrated in Figure 24.

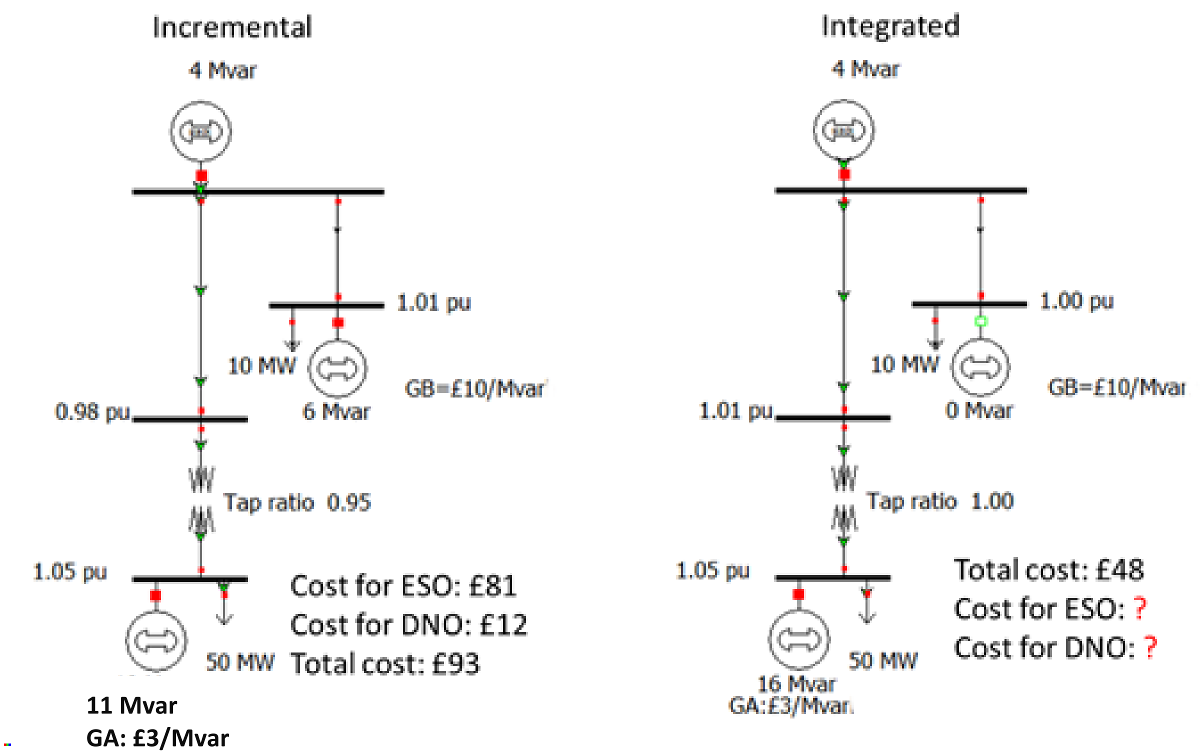



**Figure 24 Comparison between the incremental and integrated solution with no smart (preventive) control**

### 3.1.2 Smart (corrective) mode

In contrast to the preventive mode, the settings of network control devices in corrective mode can always be optimised according to the real-time system condition allowing the system to harness the maximum capability of the resources subject to network constraints. This feature should be considered since it can lower the operating cost of the system.

In the context of the case study discussed in the previous section (3.1.1), by adjusting the tap setting (back to 1 p.u.), the DSO can offer the full remaining capacity of $G_A$ 16 Mvar and $G_B$ 15 Mvar. In this case, ESO procures additional +12 Mvar from $G_A$. This costs ESO £36, and the total cost of the reactive services for both ESO and DSO is £48, the same as the cost obtained in the integrated solution. It can, therefore, be concluded that the use of smart (corrective) control can maximise the ESO access to DERs which leads to the optimal solution as obtained by the whole-system (integrated) approach. The comparison between the results of the incremental and integrated approach using the corrective control mode is illustrated in Figure 25.

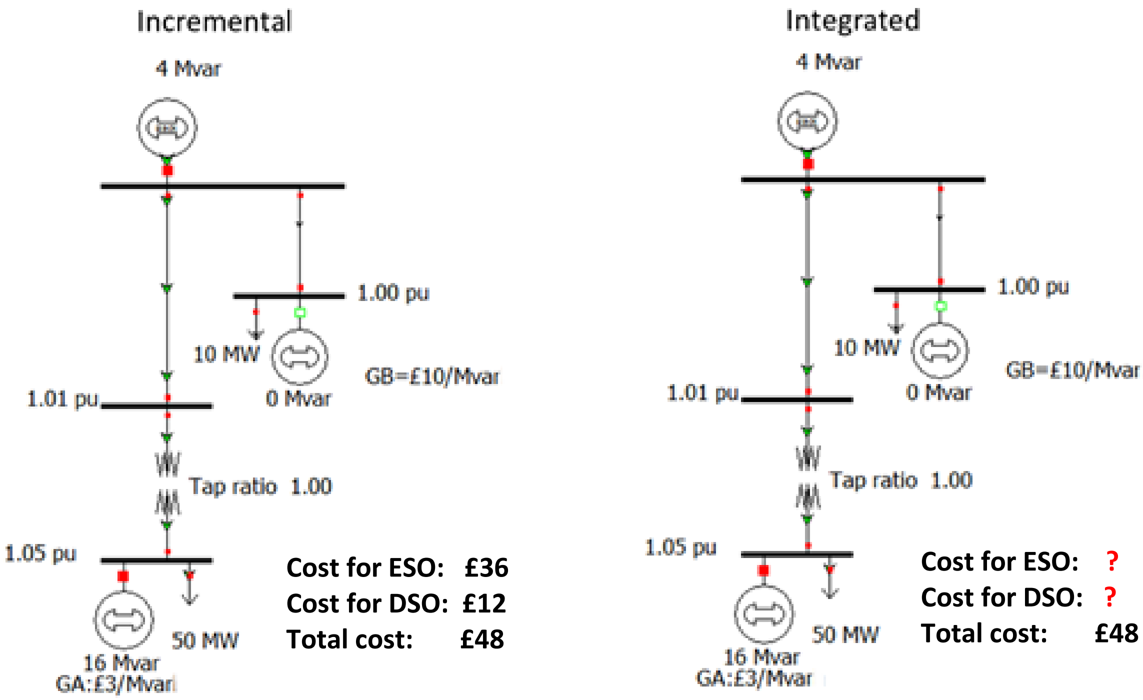



Figure 25 Comparison between the incremental and integrated solution with smart (corrective) control

## 3.2 Case studies on the Power Potential system

A similar situation can also occur on the real Power Potential system. A case has been developed to demonstrate this condition on the Power Potential network. We use high demand condition during winter with low DER output to simulate undervoltage problem at transmission and also at the distribution network. One node in the Power Potential distribution grid experiences an undervoltage problem as shown in Figure 26.

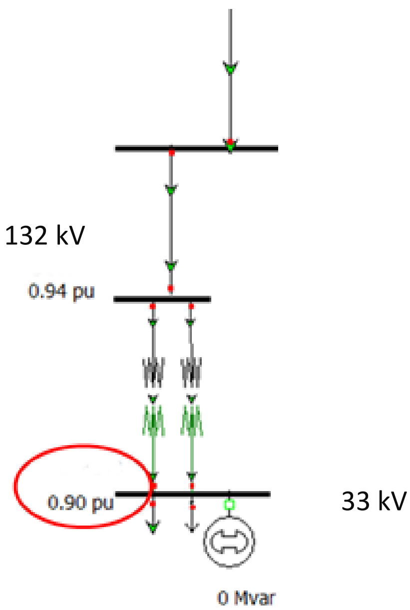



Figure 26 Undervoltage problem in Power Potential distribution grid

At the same time, ESO needs reactive services from DERs to solve the undervoltage problem at transmission especially at 400kV Ninfield substation.

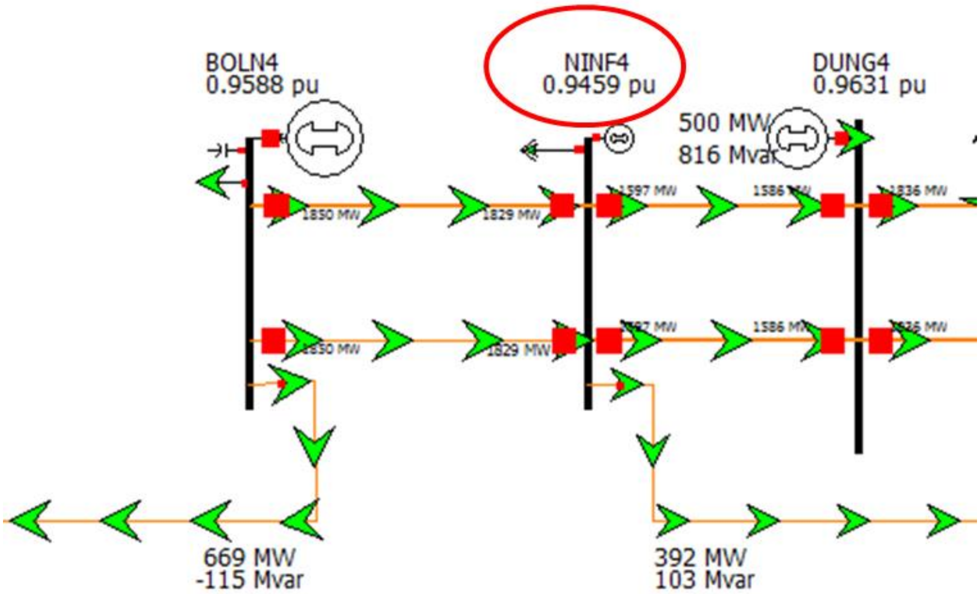



Figure 27 Undervoltage problem at the transmission

The DSO has two options to solve the problem, i.e. adjusting the setting of the 132/33 kV tap changing transformers to improve the voltage at the end of the feeder or to inject reactive power from the local generator. From the DSO perspective, the least-cost solution would be to adjust the tap setting to improve the voltage at the 33kV node. The state of the local grid after the adjustment of the transformers is illustrated in Figure 28.

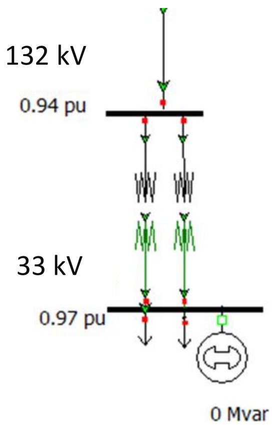
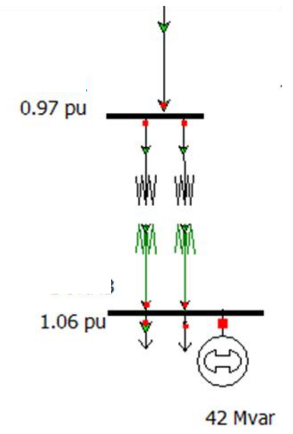



Figure 28 DSO solves the undervoltage problem in Bolney using tap changing transformers

While the DSO minimises its cost by not using the reactive services from the local generator but by adjusting the setting of the tap changing transformers, this operating decision reduces the volume of reactive services that can be delivered by the local generator to the grid. Before the tap adjustment, the local generator can inject up to +70 Mvar to the grid. At this point, the voltage at the local node will reach the upper limit (1.06 p.u.). After the tap is being adjusted, the amount of Var that can be injected from the local generation is only +42 Mvar; at this point, the voltage at the local node will be at the upper limit (1.06 p.u.). This condition is illustrated in Figure 29

**After DSO tap adjustment***




Due to DSO's control action, the resources that ESO can access from the local generator decreases by 28 Mvar.
*assuming the tap setting is operated in a preventive mode.

**Before DSO tap adjustment**

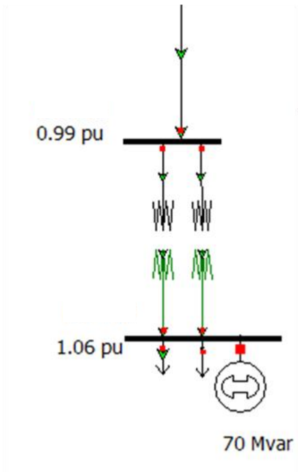



**Figure 29 Impact of different settings of transformers on the maximum reactive capability that can be delivered by the local generator**

Assuming the local generator offers the lowest price for the reactive services, ESO will need to purchase from DERs with higher prices and this will increase the overall cost of the system. However, if the tapchanging transformers are operated in a corrective mode, the setting can be re-adjusted to harness the maximum capability of the DERs which, in turn, will minimise the cost.

## 3.3 Pros and cons of preventive and corrective modes

Based on the studies and the analysis carried out, we summarise the pros and cons of preventive and corrective modes. The analysis suggests that most of the voltage control devices at transmission and distribution already operate in a corrective mode with an automatic voltage regulator to maintain the voltage at the controlled node to be within the allowed range. A similar approach can be applied to DER reactive services. In a preventive mode, DERs will provide reactive power, either lagging or leading to maintaining the system voltages during intact and contingent conditions. Although this leads to higher utilisation of DER services as contingencies usually are rare events, the preventive approach can ensure that when the contingency occurs, the voltages are kept within the limit and no direct ESO/DSO intervention would be needed. In contrast, the corrective mode provides maximum flexibility of setting the control devices to adapt to the real-time operating conditions. Thus, it will involve less reactive services, but it would require a sufficiently fast control system to adjust the settings of reactive sources and voltage control devices to respond to the system requirements in real time. The pros and cons of implementing preventive and corrective control are summarised in Table 3.

Table 3 Comparison between the characteristics of preventive and corrective modes

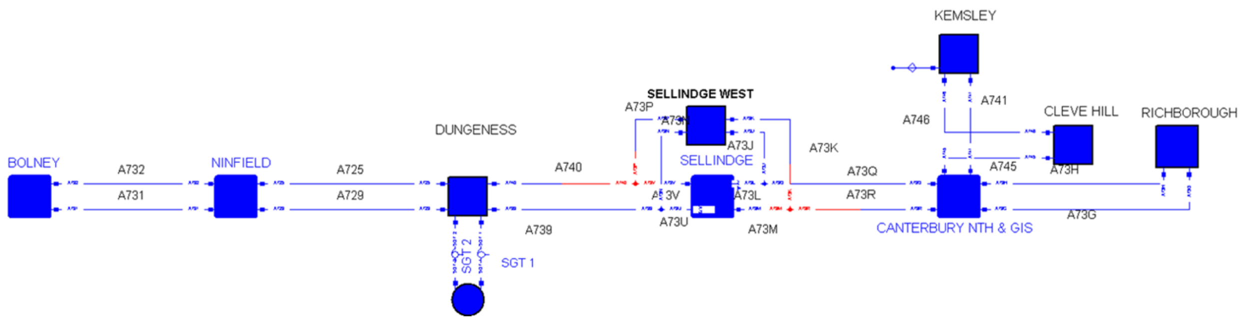
| Preventive | Corrective |
|---|---|
| No need for immediate post-fault action | Need immediate action to restore security; Benefit from automation |
| No violation in operating limits | Operating limits may be temporarily violated |
| No time limit | Operating states of the system must be restored within a certain time limit, e.g. voltages at 400kV can be between +5% and +10% for 15 minutes. |
| Risk of reducing access to DER capacity | Maximise access to the resources as the control settings are adaptive to network conditions |
| Higher cost | Lower cost |

The analysis carried out demonstrates that the preventive settings should be calculated carefully in order not to restrict the ESO access to DERs. The modelling confirms through examples that a suboptimal preventive setting of transformers can limit the reactive capacity of DERs that can be used by ESO. If this happens, ESO would need to use out-of-merit resources to solve transmission voltage problems. Using the corrective control approach, DSO would maximise the availability of the DER reactive capability to ESO, as the settings are always optimised based on the real-time system condition.

# Chapter 4. Impact of transmission outages on distribution constraints

The incremental approach assumes that the analysis of the transmission and distribution system can be carried out separately. The objective is to reduce the size and complexity of the system in question which in turn will enable quicker analysis and computation. This approach is quite practical considering the radial nature of the distribution network. Given that the Power Potential distribution systems, especially at 132 kV are interconnected via a tie-line, we have carried out an analysis to see the impact of the contingencies on the transmission systems on distribution and transmission system constraints in the Power Potential area in order to identify voltage and circuit-capacity problems.

Figure 30 shows the transmission system model of the South-East GB system and the list of thirteen single and five double circuit contingencies used in the analysis.




**Double circuit outages:**

- BOLN4-NINF4: **A732 +A731**
- NINF4-DUNG4: **A725+ A729**
- CANT4-KEMS4 / CANT4-CLEH4: **A741+A745**
- CANT4-KEMS4 / KEMS4-CLEH4: **A741 + A746**
- CANT4-RICH4: **A73H + A73G**

**Single circuit outages:**

- A732
- A731
- A725
- A729
- A739 + A73N + A73U
- A740 + A73V + A73P
- A73M + A73R + A73K
- A73J + A73Q + A73L
- A741
- A745
- A746
- A73H
- A73G

**Figure 30 Transmission system model and the list of critical single and double circuit contingencies**

Sixteen system backgrounds taking into consideration the seasonal variation in loads, DER output, different interconnection flows scenarios, and availability of the generating units in Dungeness are used for the contingency analysis. We use the winter peak demand as a reference demand (100%) and develop other demand scenarios by scaling down using the following factors: 80% for the winter high, 40% for the summer low, and 30% for the summer very-low demand. The scenarios used for the analysis are summarized in Table 4.

**Table 4 Comparison between the characteristics of preventive and corrective modes**

| | | | | | Interconnection | |
|---|---|---|---|---|---|---|
| Scenario | Season | Demand | Dungeness | DER output | Flows | Export/Import |
| 1 | Summer | Low | In | High | Low | Import |
| 2 | Summer | Low | Out | High | Low | Import |
| 3 | Summer | Very low | In | High | Low | Import |
| 4 | Summer | Very low | Out | High | Low | Import |
| 5 | Summer | Low | In | High | Low | Export |
| 6 | Summer | Low | Out | High | Low | Export |
| 7 | Summer | Very low | In | High | Low | Export |
| 8 | Summer | Very low | Out | High | Low | Export |
| 9 | Winter | High | In | Low | High | Import |
| 10 | Winter | High | Out | Low | High | Import |
| 11 | Winter | Peak | In | Low | High | Import |
| 12 | Winter | Peak | Out | Low | High | Import |
| 13 | Winter | High | In | Low | High | Export |
| 14 | Winter | High | Out | Low | High | Export |
| 15 | Winter | Peak | In | Low | High | Export |
| 16 | Winter | Peak | Out | Low | High | Export |

The constraints in transmission and distribution networks activated by the transmission circuit outages are summarized in Table 5. All active constraints are related to line overloads; most of them are at the distribution system. We observe that voltages are within the operating limits except in scenario 13-16; the results indicate maximum power transfer problems driven by voltage-collapse conditions. There is a need for voltage support to improve the power transfer capability of the system. Some constraints highlighted in bold in Table 5 are consistent with the current active constraints observed by UK Power Networks.

**Table 5 Constraints triggered by transmission circuity outages**

| Element | Category | Location |
|---|---|---|
| BOLN4 ( 1) -> NINF4 ( 2) CKT 2 at BOLN4 | Branch MVA | Transmission |
| CanterburyNorth ( 7) -> KEMS4 ( 8) CKT 1 at CanterburyNorth | Branch MVA | Transmission |
| CleveHill ( 9) -> KEMS4 ( 8) CKT 1 at CleveHill | Branch MVA | Transmission |
| SellindgeT2 ( 12) -> SELL4 ( 5) CKT 1 at SellindgeT2 | Branch MVA | Transmission |
| **APRD11 ( 78) -> RUCK1 ( 93) CKT 1 at APRD11** | **Branch MVA** | **Distribution** |
| BETT1 ( 127) -> ETCH1A ( 121) CKT 1 at ETCH1A | Branch MVA | Distribution |
| BETT1A ( 125) -> BETT1B ( 126) CKT 1 at BETT1B | Branch MVA | Distribution |
| BETT1B ( 126) -> BETT1 ( 127) CKT 1 at BETT1 | Branch MVA | Distribution |
| ETCH1A ( 121) -> ETCH1F ( 129) CKT 1 at ETCH1F | Branch MVA | Distribution |
| ETCH1B ( 120) -> SELL1A ( 92) CKT 1 at SELL1A | Branch MVA | Distribution |

| Element | Category | Location |
|---|---|---|
| ETCH1F ( 129) -> CANT1 ( 98) CKT 1 at CANT1 | Branch MVA | Distribution |
| **HAST11 ( 75) -> RYEG11 ( 76) CKT 1 at HAST11** | **Branch MVA** | **Distribution** |
| LEWE1 ( 70) -> SERX1 ( 51) CKT 1 at LEWE1 | Branch MVA | Distribution |
| NINF1 ( 59) -> POLE1B ( 60) CKT 1 at NINF1 | Branch MVA | Distribution |
| POLE1B ( 60) -> NINF1 ( 59) CKT 1 at NINF1 | Branch MVA | Distribution |
| RICH1 ( 108) -> BETT1A ( 125) CKT 1 at BETT1A | Branch MVA | Distribution |
| RICH1 ( 108) -> ETCH1D ( 119) CKT 1 at ETCH1D | Branch MVA | Distribution |
| **RUCK1 ( 93) -> SELL1A ( 92) CKT 1 at RUCK1** | **Branch MVA** | **Distribution** |
| RYEG11 ( 76) -> HAST11 ( 75) CKT 1 at HAST11 | Branch MVA | Distribution |
| SELL1 ( 88) -> SELL1A ( 92) CKT 1 at SELL1 | Branch MVA | Distribution |
| SELL1A ( 92) -> RUCK1 ( 93) CKT 1 at SELL1A | Branch MVA | Distribution |
| SERX1 ( 51) -> LEWE1 ( 70) CKT 1 at SERX1 | Branch MVA | Distribution |
| WILD1A ( 65) -> POLE1B ( 60) CKT 1 at POLE1B | Branch MVA | Distribution |

Figure 31 illustrates the effect of transmission circuit outages on the distribution network. The lost of two 400 kV circuits between Bolney and Ninfield leads to higher flow at the 132kV tie line connecting the Bolney GSP and Ninfield GSP (SERX1 – LEWE1).

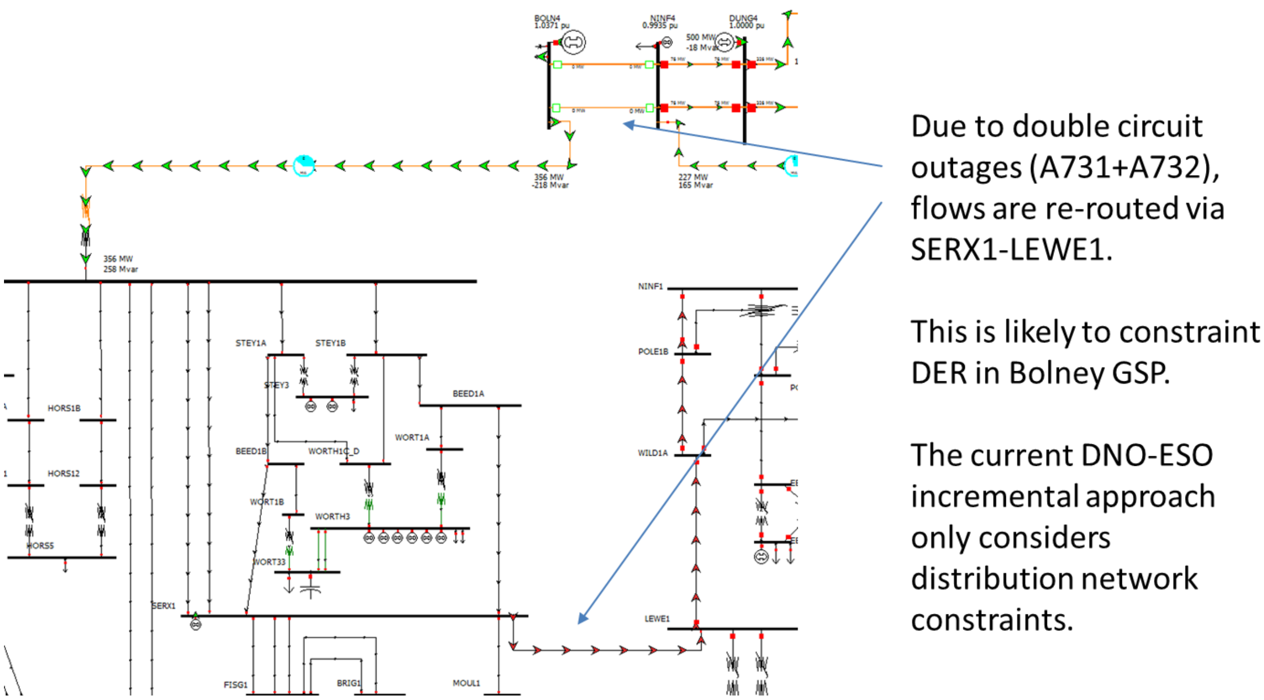



Figure 31 Impact of transmission outages on the distribution system

the impact of transmission outages should be considered in the Power Potential framework when calculating/aggregating the DER capacity that can be offered to transmission. The studies demonstrate that transmission outages, particularly, double circuit outages can exacerbate distribution network constraints which may reduce the capability of the Power Potential VPP[14]. A possible extension of the Power Potential project is to use of DER services not only for supporting voltages but also for network flow management at distribution[15].

[14] Currently, the impact of transmission outages is not considered in DERMS.

[15] An active power service within the Power Potential framework uses DER to manage transmission thermal constraints and system balancing.

# Chapter 5. Benefits of Power Potential in reducing market power in reactive power services

## 5.1 Context

Voltage control and reactive power requirement are local phenomena. Reactive power cannot be transported over long distance as it requires a large voltage difference between the corresponding network sites. Considering the operating voltages are kept within a small range (5% - 10% of nominal voltages), this restricts a long-distance reactive power transfer. Large reactive power flows also increase losses substantially and therefore it is not efficient to transport large amount of reactive power over long distances. However, reactive power is critical for the system to maintain voltage constraints and to enable long-distance active power transfers; therefore, sufficient reactive power should be provided close to the place where it is needed.

Traditionally, large-scale generating units provide reactive power services to ESO. However, there are parts of the system where the number of large-scale generating units is not sufficient to facilitate competition in the provision of reactive power services. In this situation and when the reactive power is procured through a market mechanism, there is an opportunity for a certain resource (or a group of resources) to have market power, i.e. the ability to dictate the market prices above those that would be established by a competitive market as there is no other alternative source that can provide the same level of service needed by the system. The market power related to voltage constraints management could be exercised through changing active power outputs; for example, a generator placed in a critical area could increase its income from strategically bidding in active power market, as it would need to be scheduled to operate because of the voltage problem.

A unique solution is offered via the Power Potential project, as it enables medium and small-scale DERs to provide the services. Since DERs are distributed across the area, and their number is relatively large compared to the large-scale units (although their sizes are smaller), there is an expectation that this will improve market competition in providing reactive services and reduce the possibility of having market power.

To provide quantitative evidence of the benefits of the Power Potential project in reducing market power, we have carried out a range of analysis using a Herfindahl-Hirschmann (H) index as a measure for the market concentration of reactive power resources. Below 1000, the H index indicates that there is a sufficient number of similarly sized resources that can provide the services and hence, it is unlikely for a market player to have market power. Between 1000 and 1800, the H index suggests that there is a mild concentration of resources which increases the risk of having market power.

Beyond 1800, the resources are quite concentrated, and the likelihood of having a market power is high.

## 5.2 Methodology to calculate the Herfindahl-Hirschman index

The Herfindahl-Hirschman index (H) is a commonly accepted measure of market concentration. It is calculated by summing up the square of the market share of each market participant. Expressed in percentage, it can range from close to zero to 10,000. The percentage notion is omitted.

The H index can be calculated using the following equation:

$$H = \sum_{i=1}^{N} s_i^2 \tag{1}$$

Where

- N is the number of market participants
- s is the market share of each participant

The following steps are used to calculate the H index.

Step 1. Solve a base case power flow

Step 2. Determine the voltage sensitivity of the target bus with respect to the reactive power injection at every generator in the system in turn

Step 3. Find the maximum voltage change that can be influenced by each generator by multiplying the reactive capacity of each generator with the voltage-sensitivity factor

Step 4. Calculate the market share (s)

Step 5. Find the H index

While the method is relatively simple to calculate and considers the effectiveness of a reactive power source to change the voltage at a target bus, the method also has some limitations, e.g.:

- No consideration of thermal or voltage constraints
- Ignore the impact of MW on voltages and the linkages between MW and Mvar

These limitations may not be an issue if the capacity of the resources is not severely constrained by those operating constraints.

## 5.3 Market power assessment of the system without Power Potential

Using the approach described above, we calculated the H index in the system where DERs do not participate in the provision of reactive power services. This resembled the condition before the implementation of Power Potential.  There are five 400 kV nodes of interest, i.e. Bolney, Ninfield, Sellindge, Canterbury North, and Richborough. For this analysis, high winter demand condition with high import from interconnectors is used. The H index for those nodes is shown in Figure 32.

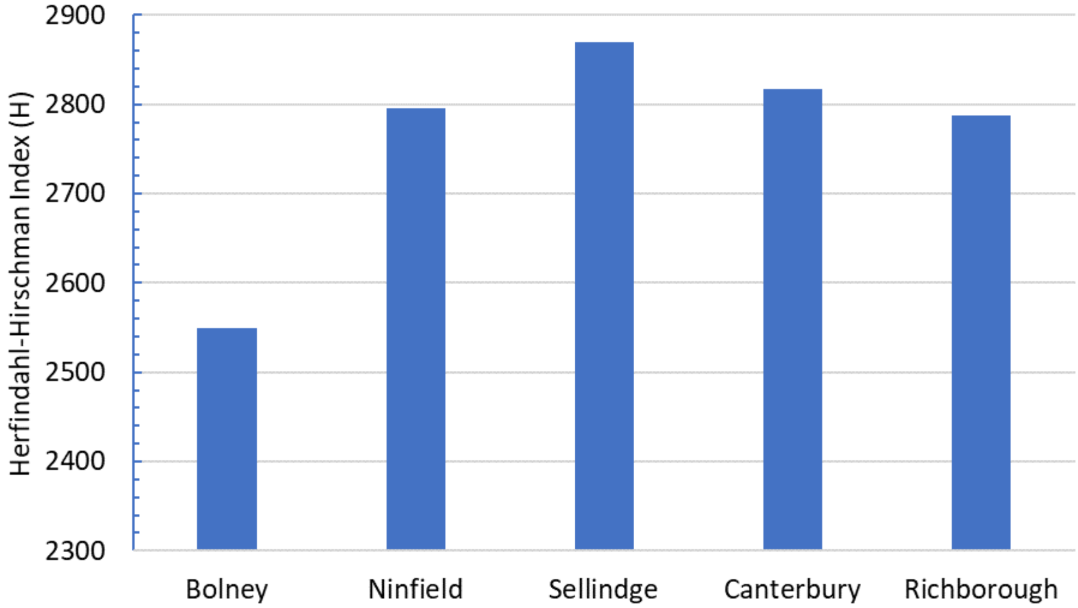



**Figure 32 H-index of reactive power concentration before Power Potential**

The results show that the H index for those GSPs is between 2540 and 2860 indicating a concentrated market of reactive power resources. These results are expected since in these areas, there are only a few reactive power sources from large-scale generators, and therefore, there is an opportunity for exercising market power. It is important to note that transmission reactive compensation devices are excluded from this index as these are not competing in the market.

This can be observed more clearly in Figure 33 which shows the market share of each market participant in the system. In this case, only large-scale reactive providers are considered; the services from DERs are not taken into account since DERs have no access to reactive services before the implementation of the Power Potential project. The name and location of generators at the x-axis are replaced by generic data (G1, G2, etc.) as data are commercially sensitive. Figure 33 demonstrates that the market share of reactive services in the area under investigation is dominated by a few (six) large-scale providers; one provider even has a market share of ~40% and above. This indicates that the system relies strongly on that specific reactive provider (or a few) which raises opportunities for those market participants to exercise their market power and dictate the prices of using their reactive services.

Reliance towards a small number of resources to provide crucial services will not only increase the system cost but also pose additional risk to the integrity of the system and reduce the system resilience towards contingencies as those resources may not be available when the system needs it.

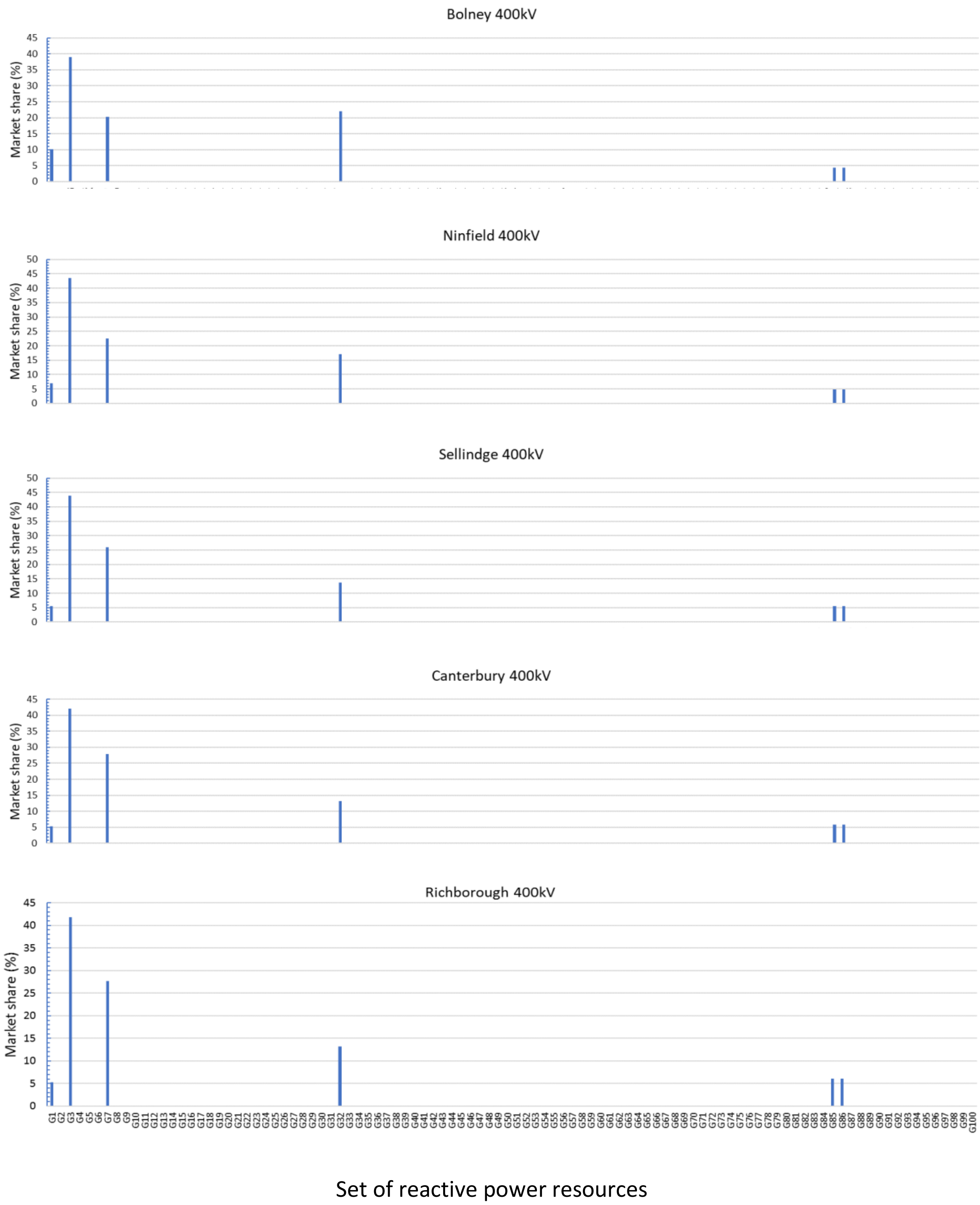



**Figure 33 Market share of reactive power resources from large-scale providers**

We observe that the market shares of each participant for different nodes are similar as they are relatively in the close electrical distance.

## 5.4 The benefit of Power Potential in reducing market power

To evaluate the benefit of the Power Potential in improving the competition in the reactive power market for the SE GB transmission, we carried out another case study allowing DERs to provide reactive services to support transmission voltages. Figure 34 shows the H index for five GSPs (Bolney, Ninfield, Sellindge, Canterbury North, and Richborough), considering the locational aspect of reactive power and voltage control, for two different conditions, i.e. before the Power Potential and after the Power Potential project. From the previous analysis, we observe that before the Power Potential, reactive power resources at these locations are quite concentrated and dominated by large service providers. The H index before Power Potential also indicates that there is not enough competition providing the reactive and voltage control services in these regions.

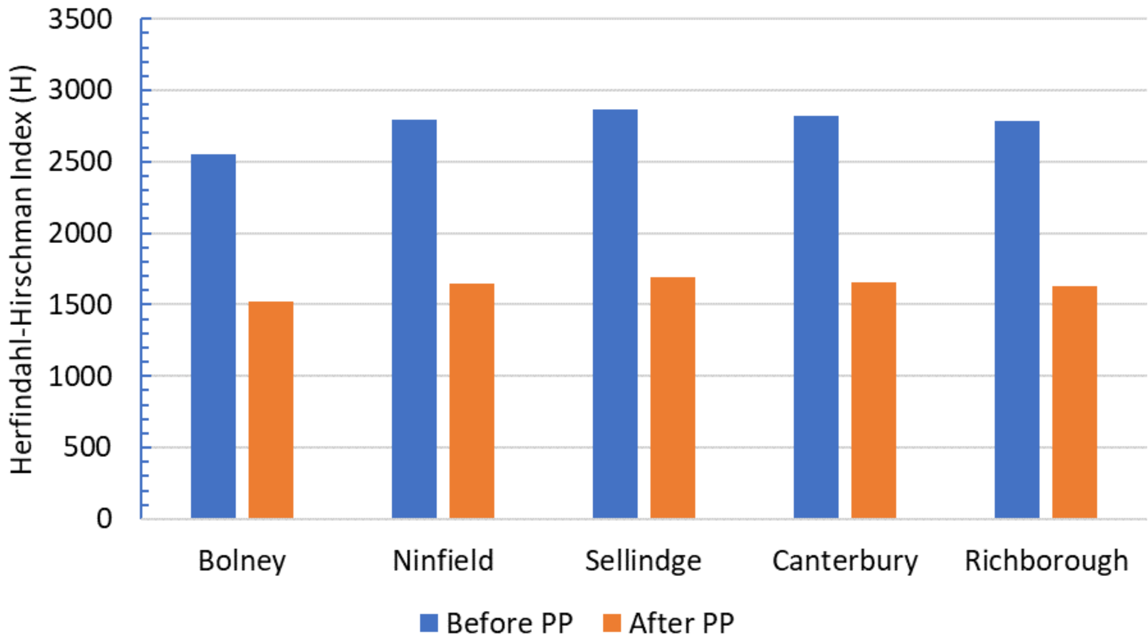



**Figure 34 H-index before and after Power Potential**

After the implementation of Power Potential that enables small-scale DERs to provide reactive support and voltage control services to ESO, all the H indices fall below 1800 indicating improved competition in the reactive power market. This analysis demonstrates that the participation of DERs to reactive power services in this area can increase the number of market participants, reduce the domination of large-scale resources and increase the number of resource options to ESO. However, the market index is still relatively high (medium concentration) and the design of reactive power market should be done carefully. It is expected that if there are more DERs participating in the Power Potential framework to supply reactive power and voltage control in the system, the H index will continue to be smaller.

Figure 35 shows the market share of all reactive resources in this area, from large-scale to small-scale providers. The results demonstrate that the large-scale players still dominate the market and the market share for DERs is still relatively small (few percents); however, it already reduces the domination of large-scale players and improves the competition in providing these services. The market share of the largest resource provider reduces from ~40% (and above) to ~30%.

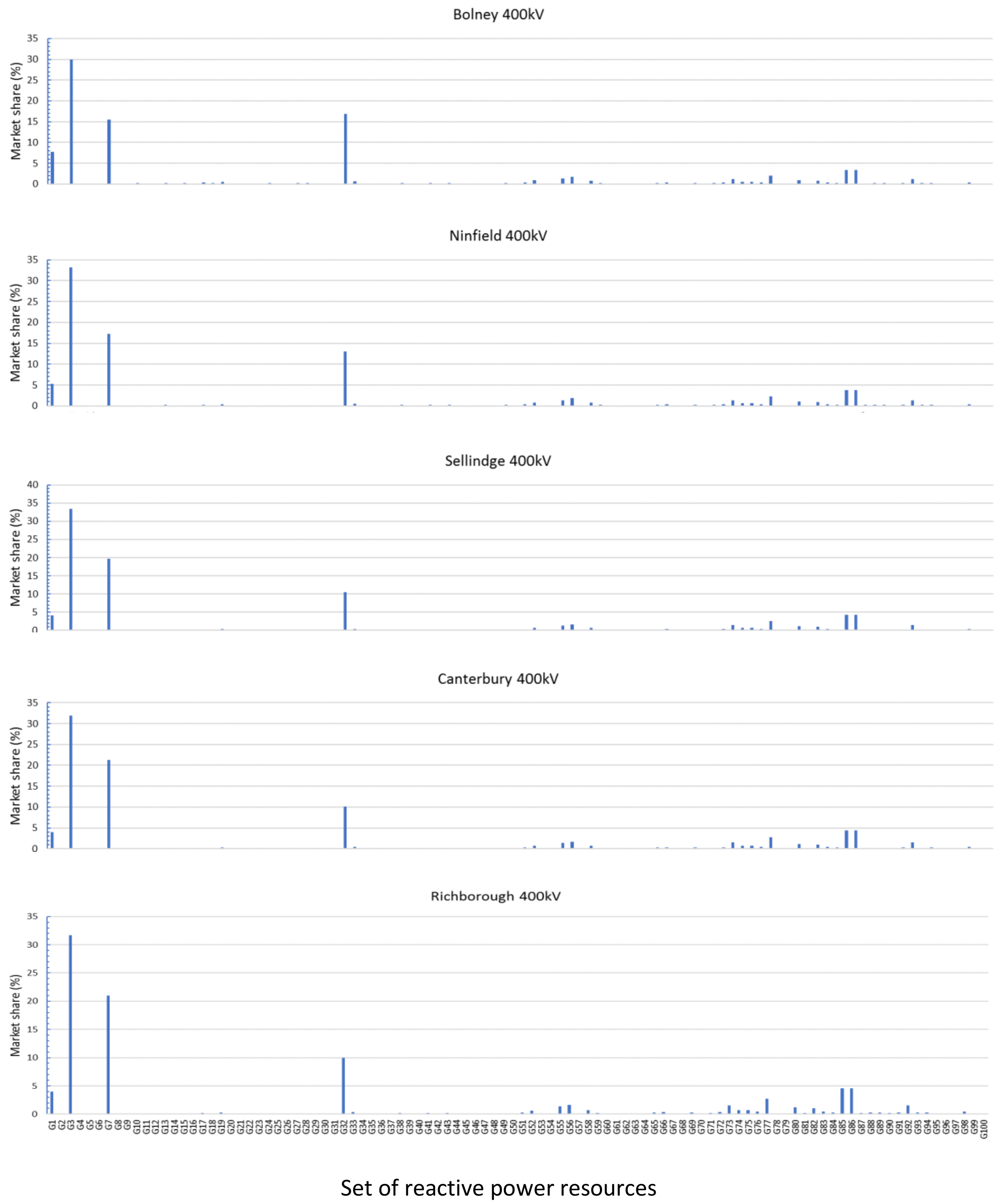



**Figure 35 Market share of reactive power resources from large, medium and small-scale providers**

## 5.5 The implication of DER market aggregation

The aggregation of DER capacities taking into consideration local distribution network constraints opens an opportunity for market integration. The aggregator can use its DER portfolio to influence the market price in order to get better revenue for DERs. In that context, we analyse how the H index will change if the DERs in each GSP are aggregated and participate in the reactive power market as a single entity. The results of the analysis are shown in Figure 36.

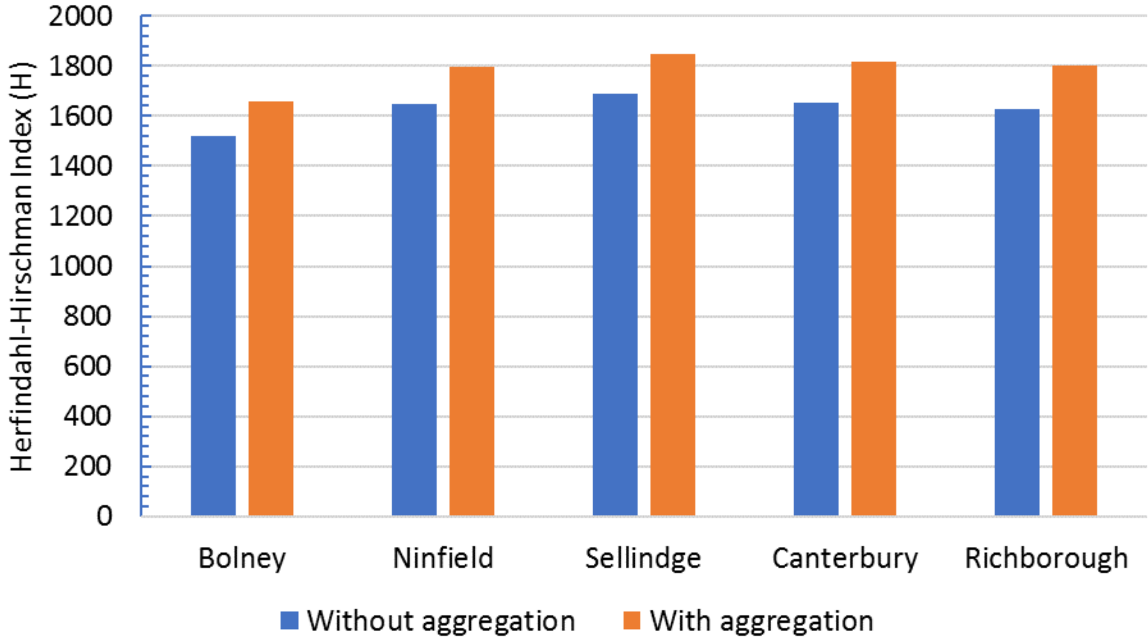



Figure 36 Impact of DER market aggregation on the H index

The results demonstrate that the H index increases in the case with DER market aggregation. It can, therefore, be concluded that the market aggregation of DER reduces the competition, increases the concentration of resources and the likelihood of market power from the system perspective. However, from the DER's point of view, the market aggregation will increase their competitiveness and market power leading to a higher revenue stream.

## 5.6 Dynamics of the market power index

As the reactive requirement in the system changes dynamically following the changes in the system operating condition, the market share of each reactive provider also varies in real-time depending on the generation scheduling, network condition, interconnection flows, and load conditions. In order to illustrate this phenomenon, a new case was developed by modifying the reference case (used for the study in section 5.3) to have low-import (500 MW from IFA and 500 MW from NEMO) and a 400 kV transmission circuit outage between Bolney and Ninfield.  In this case, the system will be stressed and experience undervoltage problems across the system as shown in Figure 37.

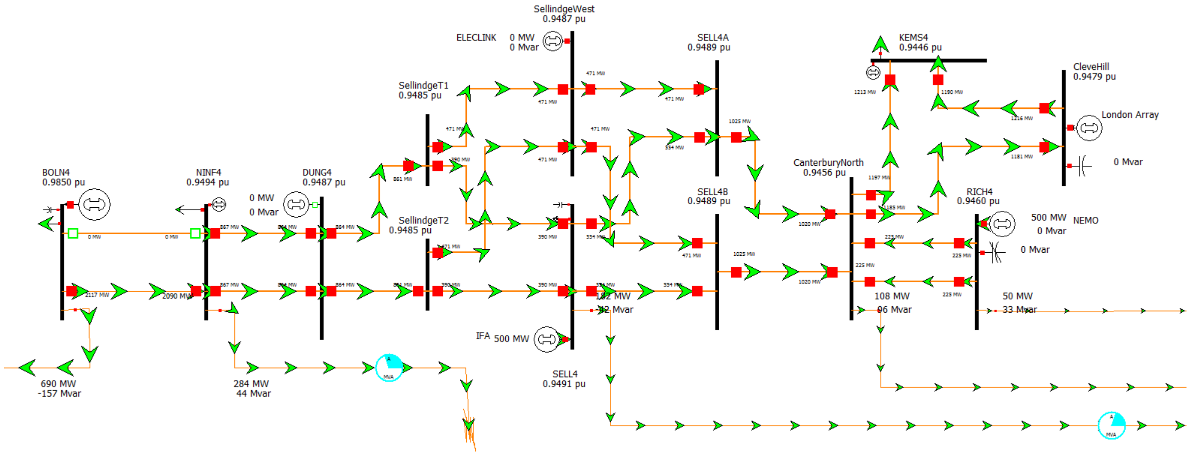



Figure 37 A system with high demand (winter), low import, and a 400 kV circuit outage between Bolney and Ninfield

Figure 38 demonstrates that the H index increases in the new operating condition. As the reactive requirement in the system increases, indicated by undervoltage problems, the market share of large providers increases and this increases the concentration of reactive resources as reflected by the H index.

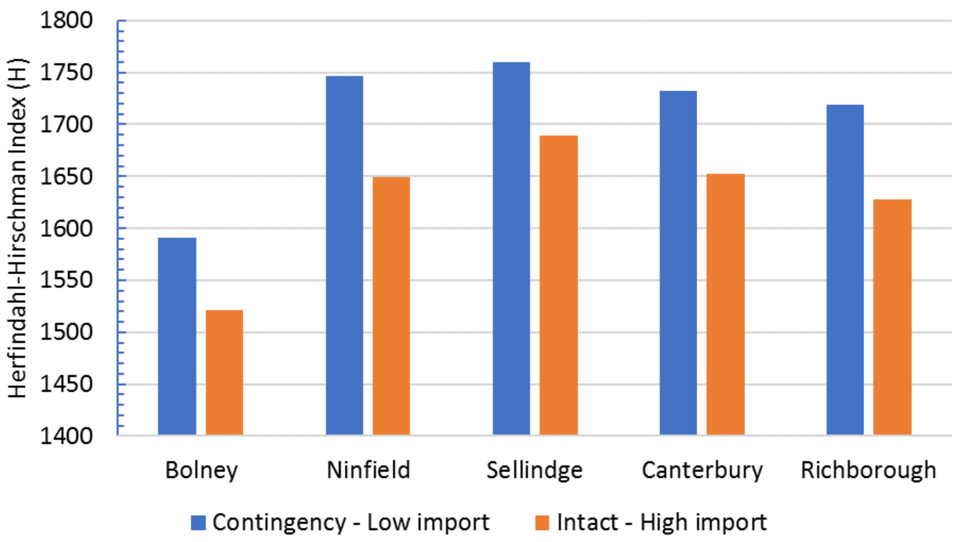



Figure 38 Impact of DER market aggregation on the H index

It can be concluded that during the stressed system conditions, there is a tendency that the likelihood of having market power increases.

## 5.7 Market power issue at a local distribution network

In the first phase of this project, we observed that the distribution networks used in the study are relatively strong which facilitate competition across DERs to provide reactive services to transmission. The number of DERs that can potentially provide reactive support is also sufficiently large, and therefore, the likelihood of DERs to have market power is small.

However, for the use of DERs to provide reactive services to distribution, this may not be the case. As the voltage problem is a local phenomenon, and the number of local reactive providers that can be used to solve the voltage problem will be much smaller; this raises an opportunity to have market power. In order to demonstrate this case, we developed an example below.

The example focuses on one area of the Bolney distribution network. The load at node A 33 kV was modified to be high enough to create an undervoltage problem at node A (top diagram of Figure 39). There is a fictitious generator installed at node A for the sake of this example. We then calculated the market share of each reactive providers in the system to control the voltage at node A; the results are shown in the bottom diagram of Figure 39.

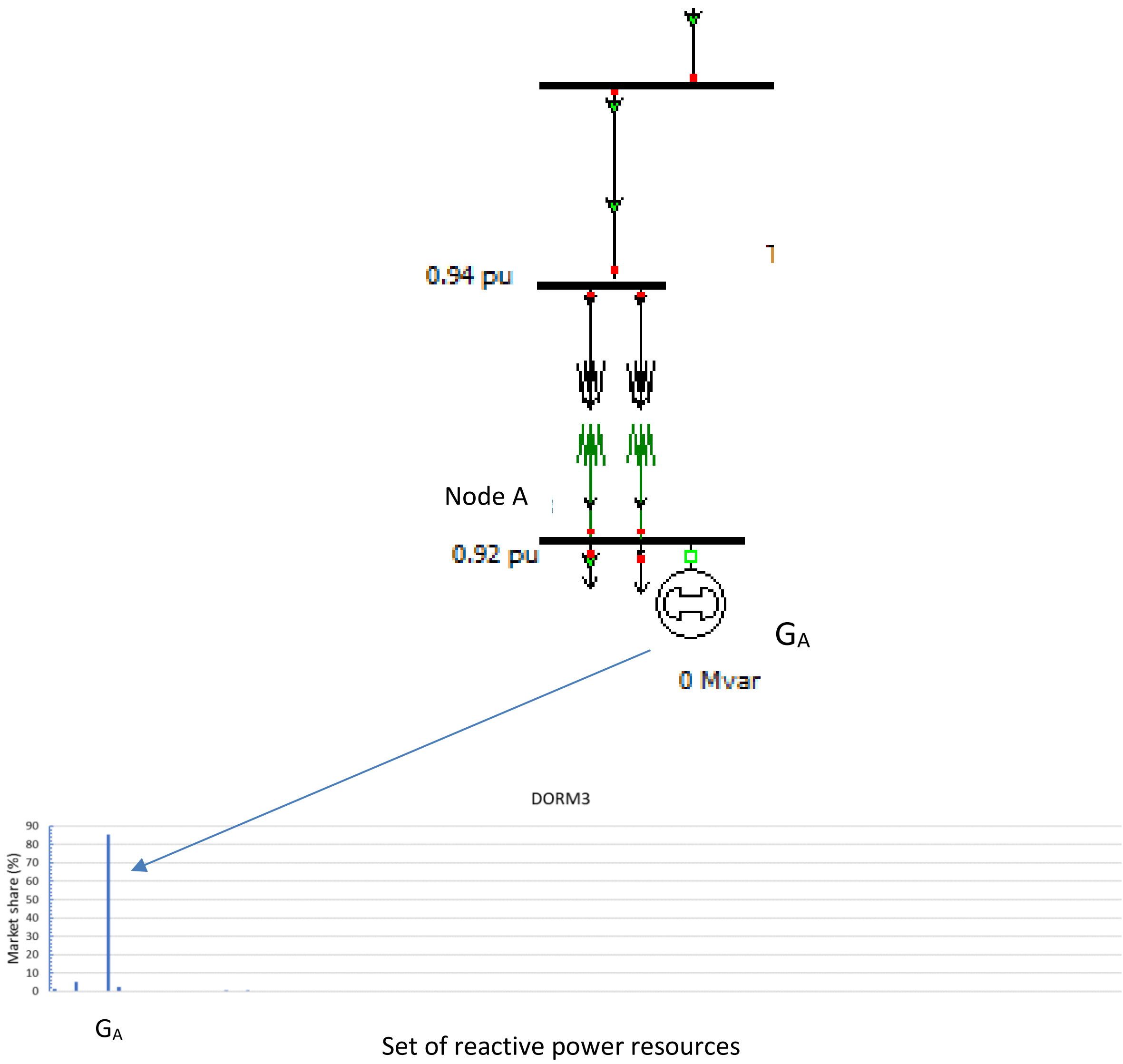



**Figure 39 Market share of reactive power resources to solve a voltage issue at a local distribution network**

Given that the generator at node A is the closest reactive power resource, its effectiveness to control voltage at node A is the highest and therefore, its market share is very high (~85%); other generators located far away from node A are not effective to solve the voltage problem at node A. Since the market to control voltage at node A is dominated by the local generator, the H index of such system is above 7000. This indicates a high concentration of the resources, and therefore, the local generator has market power. In this case, the price of the reactive services from the local generator should be regulated since there is no market competition in this case.

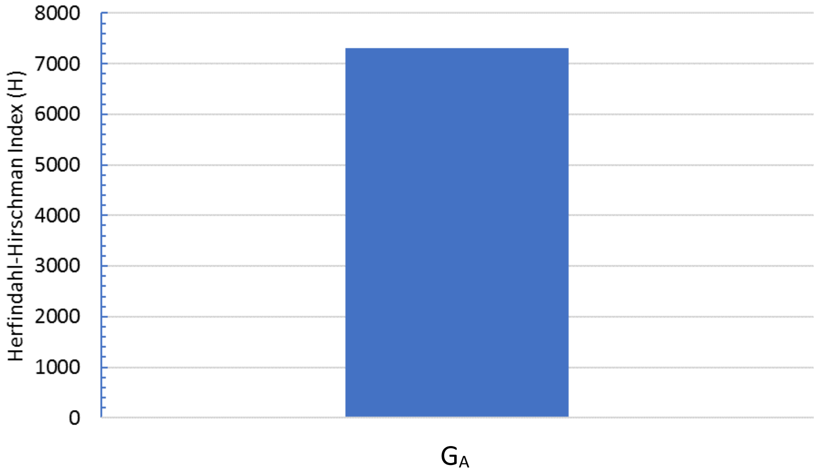



**Figure 40 Impact of DER market aggregation on the H index**

# Chapter 6. Conclusions

The key lesson learnt from analysing the results of a range of studies that have been carried out can be summarised as follows:

**Synergy and conflicts between DSO and ESO-based DER services**

- Non-coordination between ESO and DSO may trigger conflict and lead to over procurement of DER services that increase the cost of services substantially.
- There are opportunities for synergy between ESO and DSO as in most cases, both systems may experience the same voltage problems, and therefore, there are opportunities to use the same DER reactive services to solve both transmission and distribution problems concurrently.

**Comparison between Power Potential's incremental versus whole-system approach**

- The ESO-DSO incremental approach, by design, will have less coordination opportunity with DSO control and commercial decision since ESO selects the use of DERs on the basis of its cost and efficiency towards transmission problem without considering the DSO's problems. Therefore, the ESO centric solution may trigger a violation of distribution network constraints and tends to be less optimal than the solution from the DSO – ESO incremental approach.
- The whole-system coordination (integrated approach) will always produce the least-cost solution and maximise the synergy of using DERs for both transmission and distribution; however, the cost allocation for the services to ESO and DSO cannot be efficiently determined as in the incremental approach.
- DSO-ESO incremental approach (Power Potential concept) provides a pragmatic alternative solution to the whole-system approach as it delivers a balance between complexity, practicality, transparency, and optimality of the results. The solution from DSO – ESO incremental coordination (Power Potential approach) tends to be similar to the solution from the integrated approach since DERs will have a higher locational impact on local distribution compared to transmission; therefore, solving the distribution problem first seems to be a reasonable approach as indicated by the results of the case studies carried out.

**Importance of DSO led smart control in distribution to maximise access for DERs to ESO and the implications of preventive or corrective control modes on the ESO - DSO coordination**

- Non-smart (preventive) control by DSO may restrict the access to DER capacity for ESO which leads to a higher cost. The least-cost solution for DSO may not be the least-cost solution from the whole-system perspective.
- Use of smart control to maximise access for ESO to DER capacity is recommended for the Power Potential framework. The smart control (corrective mode) provides maximum flexibility of setting the control devices to adapt to the real-time operating conditions. Thus, it will involve less reactive services, but it will require a sufficiently fast control system to

adjust the settings of reactive sources and voltage control devices to respond to the system requirements in real time.

### Impact of transmission outages on distribution constraints

- Contingency studies demonstrate that faults at transmission can trigger active constraints at distribution which are mostly in the form of thermal limit violation. This needs to be considered in the incremental approach especially when the aggregated DER capacity resources that can be offered to ESO is calculated.
- A possible extension of the Power Potential project is to use of DER services not only for supporting voltages but also for network flow management at both transmission and distribution.

### Benefits of Power Potential in reducing market power in the provision of reactive power services

- Without Power Potential, reactive power market in SE GB transmission is highly concentrated. The market of reactive services in this area is dominated by large-scale players as DERs do not have access to the reactive power market.
- Power Potential reduces market power and increases competition (moderately concentrated) as the large-scale players are now competing with DERs.
- Aggregation of DER capacity located on the DSO side may increase market power as it facilitates enhanced coordination and control of Distributed Energy Resources.
- Market power index also increases when the system is under-stressed or constrained.
- In a distribution network, the case of market power for providing reactive services tends to be stronger due to the local nature of reactive power and a relatively small number of service providers.