Enhancing transmission and distribution system coordination and control in Great Britain using power services from distributed energy resources

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Abstract

This paper describes the technical principles behind the Power Potential innovation project in Great Britain (GB). The project aims to enable distributed energy resources (DER) connected to the distribution network to provide services to the transmission grid, in a coordinated manner. The paper focuses on the dynamic voltage control and the provision of reactive services that can be exercised through these assets. The specific control principles to enable participation of different DER technologies (synchronously and non-synchronously connected) to provide transmission support are described here. Simulation studies are included to theoretically validate the proposed solution using a detailed dynamic model of the transmission-distribution network in GB. The value of this control approach as a new tool for the system operator is also highlighted and the next steps for the Power Potential project are finally summarised.

1 Introduction

Distribution power networks in Great Britain (GB) have been experiencing increased levels of new generation capacity (wind, solar, storage, etc.) in the form of distributed energy resources (DER) [1]. As the number of these elements increases and displaces conventional transmission connected plants, their potential value to provide network support, not only at a distribution but also at transmission level, will need to be explored. In this context, increased coordination between the GB System Operator (SO) and distribution network owners (DNOs) is needed to efficiently increase the power system flexibility by further utilising the DER capabilities. This work describes Power Potential: the innovation project between National Grid (the GB System Operator) and UK Power Networks (the DNO in the South East boundary of GB), which is aiming to increase network capacity using DER resources. The project is funded by the network regulator Ofgem's Network Innovation Competition mechanism and it is focused on the South East region of England (see Fig. 1). Connection of distributed energy resources is growing rapidly in this area and so it would benefit from increased flexibility from embedded assets [2].

The objective of Power Potential is to develop a technical and a commercial solution to maximise the use of DER to resolve transmission voltage and thermal constraints. The collective response from DER at transmission level will effectively be considered as an equivalent virtual power plant [3]. This paper describes the novel technical framework proposed for the coordination of the different actuators (GB System Operator, DNO and DER) in the Power Potential project. The considered solution is a world-first trial which will enable DER to provide transmission support and will develop a new power market for these resources, resolving conflict of services while creating additional revenue for DER. To enable this new control approach, a software-based system to control DER is currently being developed. This will facilitate the communication between DER connected to UK Power Networks and National Grid, for both technical, control, and commercial data. This platform, known as DERMS (Distributed Energy Resources Management System), is central to Power Potential and the control principles behind it are summarised in this paper. Two different services can be provided by DER through DERMS for managing transmission constraints: active power service and reactive power service (delivered as dynamic voltage support, equivalent to an SVC or other transmission connected plant). In particular, this paper includes a detailed description of the principles associated to the reactive power service, given that this is a novel implementation in an actual power system.

The structure of this paper is as follows. Section 2 summarizes the current efforts in the area of transmission-distribution coordination and control, highlighting the novelty of the Power Potential project. Section 3 presents the trial network area for the project in GB and describes its operational problems. Section 4 covers the control principles of the Power Potential control platform (DERMS) and includes the proposed solution for coordinating the different actuators, particularly when providing dynamic voltage support. An overview of the commercial framework associated to this solution is presented in Section 5. Section 6 introduces case studies using a detailed transmission-distribution dynamic network model. Section 7 explains the implementation process of DERMS and the project's next steps while highlighting the value of DERMS for the SO, DNOs and DER. Finally, Section 8 shares some conclusions.

2 TSO/DSO coordination for grid support

Traditionally, transmission and distribution power networks have been operated independently, with large generators connected directly to transmission being used to operate and manage the grid. As new smaller generation technologies and smart assets appear in the system replacing large plants and reducing carbon emissions, control options shift from transmission to distribution. This establishes the need for a coordinated transmission-distribution approach to operate future networks. This new philosophy has produced extensive literature covering theoretical implementations, roles, responsibilities and market options for these TSO/DSO schemes [4]. In the UK, significant work is being carried by the Electricity Network Association (ENA) to progress on this topic [5]. Although some successful examples are already in place for the coordinated delivery of active power services (e.g. frequency, balancing and constraint management services) from distribution assets [4], actual implementation of coordinated voltage control services from DER remains mostly an unexplored area. It is to be noted the efforts by the French TSO [6] and the Swiss TSO [7] on the context of transmission-distribution voltage support. These support schemes rely, respectively, on the use of distribution compensation assets and on the establishment of requirements immediately at the distribution-transmission interface. The Irish TSO is also looking at transmission voltage support from radial distribution wind farms in its nodal control project [8]. It is the aim of Power Potential to be the first world trial to test the delivery of dynamic voltage support from different types of distributed energy resources (DER) embedded at various voltage levels, operating transmission and distribution networks in a coordinated and automated manner.

3 Power Potential England South East test area

Power Potential aims to address the operational problems observed in the South East region of the transmission network in England (see Fig. 1), an area which is notably congested and would benefit from increased flexibility from embedded assets. This location has been experiencing a high penetration of DER with connection volumes growing rapidly in recent years, due to the availability of wind and solar resources in the area. Therefore, this region has a significant amount of renewable generation which could be further exploited. There is currently around 1.5 GW of connected distributed generation and 0.3 GW of contracted applications. Additionally, the transmission network in this region is connected to continental Europe via a 2 GW HVDC link (IFA to France [9]). The number of interconnections is expected to increase up to 5 GW with future projects including Nemo to Belgium [10] and Eleclink to France [11], amongst others. The network in this region also provides electricity to London, which is the largest demand centre in GB. These challenging conditions are causing voltage and thermal constraints in the transmission network, which makes operating the system for varying scenarios difficult for the GB System Operator (SO), National Grid [2]. Though Power Potential, DER will be able to provide **active power services** and/or **reactive power services** to the SO. The active power service is expected to improve the management of thermal constraints whereas the reactive power service is intended to provide dynamic voltage support, similar to an SVC or STATCOM reactive compensation device which is connected to transmission (or to a supergrid transformer tertiary).

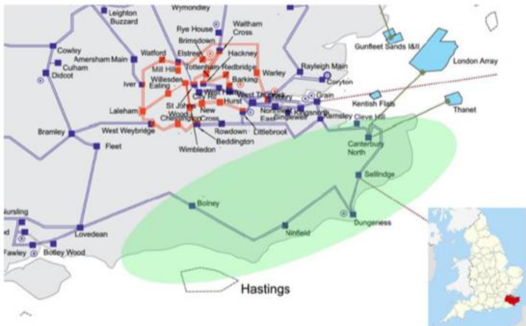

Figure 1. The Power Potential project trial region in Great Britain (GB).

Four locations where the transmission network interfaces with the distribution network in the South East area are considered within the scope of the Power Potential project. These grid supply points (GSPs) are: Bolney, Ninfield, Sellindge and Canterbury North and the proposed control solution will be trialled and evaluated here. A detailed overview of these GSPs is shown in Fig. 2. The aggregated DER response at the GSPs is represented as four equivalent virtual power plants. It has to be noted the limited number of transmission connected generation assets that provide reactive support in this area (Dungeness: 1100 MW nuclear power station – which will disappear in future, London Array: 630 MW wind farm and the newly connected Rampion: 400 MW wind farm) which also increases the need of new control options. Outside this region, generators connected at the nearby Grain substation are also used for reactive support.

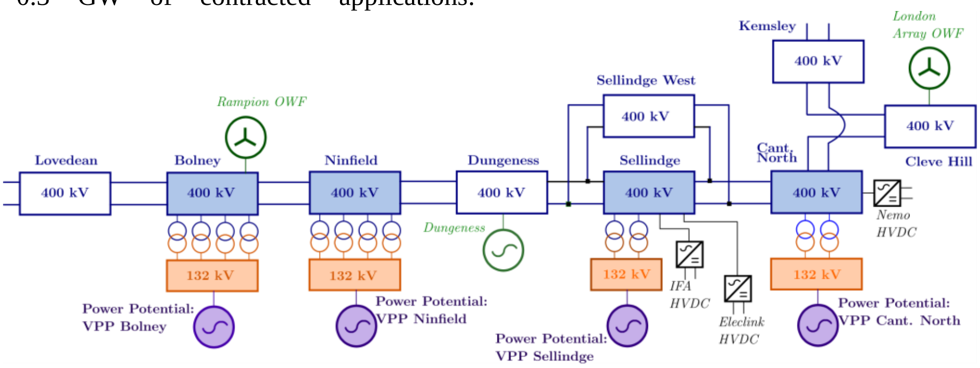

Figure 2 Transmission network and GSPs in scope for Power Potential

3.1 Voltage management concerns in South East area

As mentioned before, the topology of the transmission system and the generation mix, make this area of the system extremely challenging to operate. We focus in this work on the reactive power service of Power Potential, as this will be a novel tool for the SO to manage transmission voltage constraints using direct support from DER. Voltage constraints in this area are most prominent when a double circuit fault occurs on the route between Canterbury and Kemsley. This leaves only one long radial route to deliver energy to London which could trigger voltage stability issues that could lead to voltage collapse if not contained in time [2]. To prevent this from happening, the SO is forced to restrict pre-fault flows across this South East route. In addition, high transmission system voltages are caused by the Ferranti effect during periods of low system load and high generation from DER. Dynamic voltage support from DER will help to alleviate these constraints, avoiding generation curtailment and allowing more DER to be connected to the distribution network in this region.

4 Power Potential technical solution: DERMS

4.1 DERMS: Control platform overview

In order to address these operational challenges and actively involve DER in the system operation, Power Potential is developing and building a new control platform. This will establish communication and control between DER connected to UK Power Networks and National Grid. This control system is known as DERMS (Distributed Energy Resources Management System) and an overview of this control process is shown in Fig. 3.

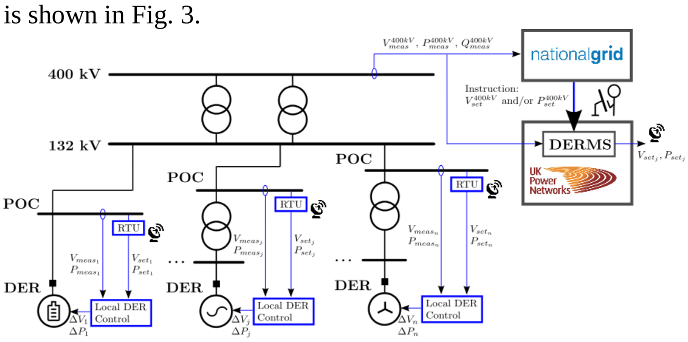

Figure 3. DERMS interface between National Grid and UK Power Networks.

This control structure allows both the provision of dynamic voltage support after system outages (post-fault response) and the instruction to DER to support the system under normal operating conditions (pre-fault response). In pre-fault conditions, instructions from National Grid to DERMS for the different services are defined at the interface points with the distribution network (i.e. 400 kV level, GSP). For the active power service, National Grid will instruct a MW volume ΔP_{400kV}^{set}. For the reactive power service, National Grid will instruct a voltage target set-point V_{400kV}^{set} with a droop characteristic and a dead-band to be delivered at each GSP. DERMS continuously calculates free capacity in the DER and the distribution network and adjusts local DER set-points to achieve National Grid instructions, at the lowest cost, without violating distribution network constraints. At DER level, a different voltage droop control is used for the reactive power service and an active power MW set-point for the active power service. In both cases, the performance site specific capability of the generator would be respected (see Fig. 4).

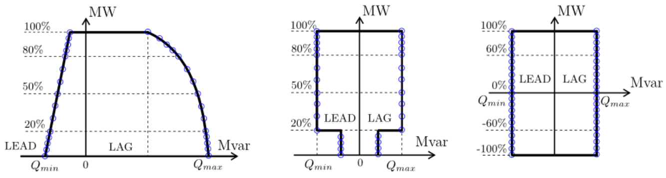

Figure 4. Examples of PQ technical characteristics for different DER technology types (synchronous, wind farm, storage).

In post-fault conditions, DER under the reactive power service will automatically deliver voltage support after a large transmission voltage change and will adjust their response to help the voltage recovery following an enhanced signal. The following sections describe the control structure behind this reactive power service. This control scheme will also enable DER to participate in a new reactive power market, to actively provide transmission voltage support services.

4.2 Local DER control

At non-synchronous DER level, each generator i will be controlled using a proportional controller, also referred to as droop (with value K_2). This control, which is typical of those found already in DER, adjusts the level of reactive power Q_i produced by the DER by measuring the local DER voltage V_i^{meas} (at the point of connection) with respect to a voltage reference set-point V_i^{set} (calculated by DERMS), according to:

$$\Delta Q_i = (1/K_2)*(V_i^{set} - V_i^{meas}) = (1/K_2)*\Delta V_i. \qquad (1)$$

This local control allows DER to automatically respond to voltage variations in the network, providing dynamic support after an event occurs (e.g. circuit fault, interconnector trip, etc.). Fig. 6 shows the local DER control block.

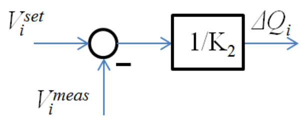

Figure 6. Local DER control.

Note that for synchronous DER, this automatic response is expected to come from the generator's automatic voltage regulator (AVR). The AVR would control the generator terminal voltage by following a voltage reference set-point V_i^{set}. This results in a droop-like control function at the high-voltage side of the generator step up transformer. Under- and over- excitation limits are expected to be in place.

4.3 Supervisory (enhanced) DER control

The local control implemented at each DER is complemented with an enhanced response calculated by DERMS. This supervisory high-level control will update the voltage set-points of the DER local controllers (V_i^{set}). This is either to achieve a reactive power response at the 400 kV transmission level (GSP) or to maintain and improve the DER support after a fault in the transmission network. The later aspect is of critical importance since, after a sudden decrease of the transmission voltage, super-grid transformers[1] (SGTs) will tap to restore the voltage in the distribution network (distribution transformers will tap as well). In these conditions, an enhanced signal is needed to maintain the support from DER after the transformers tap. Relying only on local measurements would not maintain the DER support in the longer term as the fault status of the transmission grid would not be captured.

Following a National Grid voltage set-point instruction V_{400kV}^{set}, the reactive power response required at the 400 kV level Q_{400kV}^{set} is derived from a voltage droop characteristic (of gain K_1) defined at each GSP point, as shown in Fig. 5.

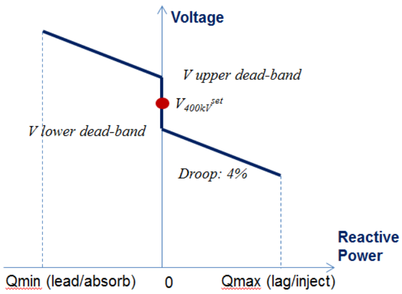

Figure 5. Voltage droop characteristic applied at each GSP.

The control system will then act to achieve the reactive power demand (at each GSP), according to:

$$Q_{400kV}^{set} = (1/K_1)*(V_{400kV}^{set} - V_{400kV}^{meas}) \quad (2)$$

$$V_i^{set} = (k_p+k_i/s)*(Q_{400kV}^{set} - \Sigma Q_{400kV}^{meas}). \quad (3)$$

where ΣQ_{400kV}^{meas} corresponds to the sum of measured reactive flows from all the SGTs associated to one GSP. k_p and k_i are the gains of the enhanced controller. This delivers a voltage droop function at each GSP in which the aggregated DER response at the interface points can be considered as an equivalent virtual power plant. The reactive limits of this curve (Q_{min}, Q_{max}) are dynamic and continuously being updated by DERMS, according to network conditions.

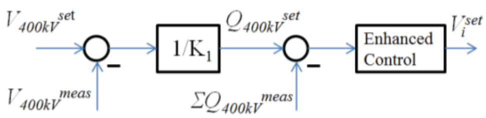

Figure 7. Enhanced DER control by DERMS.

Fig. 7 shows the DERMS control scheme at a supervisory level, which is expected for each GSP. It is important to emphasise that this solution will enable DER in the distribution network to dynamically provide voltage support (providing 90 % of the response in 2s) during system events and will also offer a new tool for the system operator to increase the voltage stability margin at 400kV.

5 Power Potential commercial solution: new regional market

Together with the technical solution, the Power Potential project is creating a new commercial framework to enable DER to participate in a new regional active and reactive power market. A short-term market is expected and it will run daily to accommodate the variability in the production of some DER participants (i.e. wind and solar). The reactive power market from distributed resources is a novel concept that will create more flexibility enabling transmission and distribution networks to operate more efficiently. A description of the commercial framework proposed for the project and its expected terms will be covered in [12]. This includes details regarding payments for service availability and use, response delivery requirements, and the contractual relationship between UK Power Networks and DER and between UK Power Networks and National Grid (SO).

6 Simulation results: theoretical analysis

Simulation results in this section theoretically validate the principles of the proposed control in DERMS. They highlight the value of the coordination scheme in a detailed model of the transmission-distribution network in Great Britain (GB).

6.1 Modelling considerations

This study uses a full detail dynamic model of the GB transmission-distribution grid to validate the DERMS control solution. The network under study resembles a future generation scenario (year 2025) where Nemo and Eleclink interconnectors will be active in the grid. The system conditions have been adjusted to show the effect of a critical contingency leading to a low voltage scenario. This means that the minimum voltage planning limit of 0.95 p.u. at Bolney GSP is reached in steady state post-contingency conditions. The circuits in the South East region are exporting power to London via the west and east connections (approximately 4 GW, 1.6 GW injection from Bolney and 2.4 GW injection from Canterbury North, see Fig. 2). The interconnectors importing around 2.7 GW. The total system demand is low and equal to 16.9 GW, making the system more prone to voltage support issues. In the South East region under study within the project, DER rated above 1 MW and connected to UK Power Networks' distribution network above 11kV are considered to provide services in Power Potential's DERMS. These generators are producing a total of 572 MW, in line with Table 1. Table 1 also shows the DER allocation per GSP[2] and includes indicative numbers of production levels. All synchronous DER and PV generators are dispatched at 100% while wind generators are dispatched at 70%. PV and wind generators are assumed to be capable of

[1] Automatic Voltage Control (AVC) schemes will automatically tap the appropriate SGTs after 30 seconds when the LV bus-bar voltage deviates beyond a +/-2% dead-band to bring the LV voltage back to target.

[2] Allocation of a DER to a particular GSP is done according to its reactive power injection effectiveness in a particular GSP (dQ_{400kV}/dQ_{DER}).

delivering reactive power up to 0.95 p.f. while synchronous DER are assumed to be rated at 0.85 p.f. No storage devices are considered in this study, although this type of technology will be accommodated in the project.

GSP	*DER number*	*Total MW*
Bolney	8	92.15
Ninfield	6	108.13
Sellindge	4	32.5
Canterbury North	9	274.95
Richborough*	6	64.2

Table 1: Number of DER considered per GSP and associated total MW rated value. *Richborough is a substation expected to be present by 2025 but which will not be considered for the Power Potential project trials.

Table 1 excludes the contribution of large embedded generators in the distribution grid (>100 MW) which are subject to different grid code requirements. Regarding the network dynamic model, DER farm controllers are represented using generic control models. The DER covered in Table 1 are considered to be under the control scheme described in Section 4. The dead-band of the DERMS supervisory control is set at 1% and the droop gain to 4% (see Fig. 5). Voltage target set-points are set to pre-fault steady-state values. Finally, shunt compensation devices in the area are considered fixed providing only static support.
Note that the results presented next are valid under the previous assumptions (and others not listed here) and do not necessarily represent an exact future network condition/response. At this stage, the intention of these results is to validate the control scheme and see the potential value of the DER contribution rather than to recreate the particular volumes expected for the Power Potential project trials.

6.2 Case Study: Response to a critical contingency

The critical contingency for the South East boundary equivalent to the double circuit outage of the 400kV transmission lines Kemsley-Canterbury and Kemsley-Cleave Hill (see Fig. 2) is simulated here. Both circuit lines are disconnected 140ms after a three-phase rigid fault occurs in the network. Fig. 8 and 9 show the system response after the fault, with and without contribution from DER. Total delays in DERMS communications (end-to-end process) can vary and are studied in a range from 1 to 10s. Fig. 8 shows the total reactive power flow variation from all the considered GSPs. After the fault is cleared, there is an increase in the reactive power export, under all the considered scenarios. Without Power Potential (black traces), the grid delivers a natural response of 72 Mvar. With Power Potential, this contribution increases up to 158 Mvar by having enabled the DER support (red traces). This additional response occurs in two stages, an automatic DER response followed by the further adjustment of the DER set-points by DERMS. This enhanced response is affected by the delays in the communications in DERMS and DER. The green curves show a 3 s delay and the blue curves a 10 s delay. It is to be noted that these delays are ultimately postponing the full DER delivery which will settle at the same value (approximately 193 Mvar, not shown in the time-scale presented in Fig. 8). Self-dispatch (local DER control) achieves 80% of the reactive response with the enhanced control allowing additional 20 % of reactive power to restore transmission voltages.

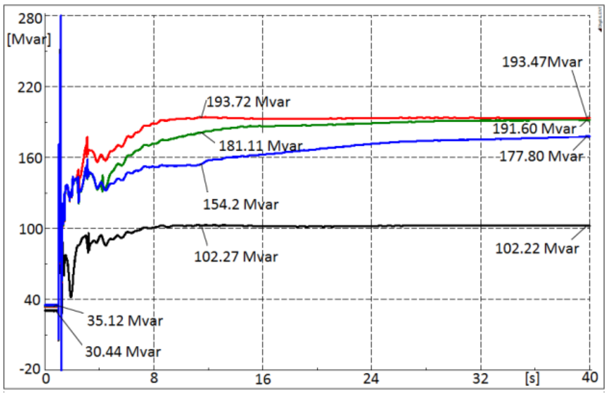

Figure 8. Total GSP reactive power injection after critical contingency: without Power Potential (**black traces**), with Power Potential – 1 s delay (red traces), with Power Potential – 3 s delay (green traces), with Power Potential – 10 s delay (blue traces).

Fig. 9 shows the voltage variation at each GSP following this critical fault, without Power Potential contribution (solid traces) and with contribution, assuming a 10s communication delay (dashed traces). After the fault, the voltage profile across these GSPs falls considerably, as this area becomes a long radial circuit with high active power export. With Power Potential support, there is an overall voltage improvement (approximately 0.006 p.u., equal to 2.4 kV at each GSP). This is in line with the reactive injections in Fig. 8.

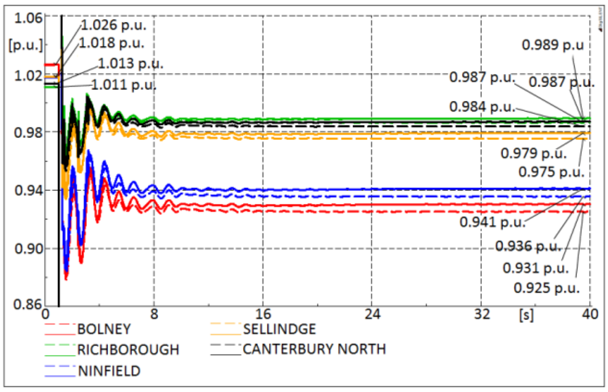

Figure 9. Voltage change per GSP after critical contingency: without Power Potential (solid traces), with Power Potential - 10 s delay (dash traces).

7 Power Potential implementation: design and build of a new transmission-distribution tool

The Power Potential project is currently building the DERMS control platform, following the principles summarised in this paper. The project team is actively engaging with potential DER participants. By mid-2018, framework agreements with those DER participants are expected to be signed after having issued a definitive commercial proposition. DERMS will be built by early 2019. This includes acceptance testing and validation. The project trials will run during 2019.

Collaboration between transmission and distribution networks companies to achieve a coordinated service which would offer value to both parties and DER participants is of critical importance together with understanding the needs of potential DER participants. DERMS is a novel tool which has required continuous discussions between DNO/TSO in order to shape the controller design. Solving existing communication delays and preventing cyber security issues when exchanging data has been identified as a critical aspect that will shape the response of the DERMS solution.

In any case, it is expected that the services (active and reactive) from Power Potential will help the GB System Operator in the following scenarios. Note that Scenarios 1 and 2 cover a unique reactive power service, driven by two different system conditions (low voltage following a fault or high voltage following low system demand). So voltage control in both scenarios is covered by the same reactive power service that provides dynamic response. Scenario 3 covers the use of the active power service.

- **Scenario 1:** ***Reactive power service to manage transmission high voltage***. The virtual power plant at each GSP will be instructed to absorb reactive power. This service is expected to be instructed (depending on market cost considerations) very frequently: 80% of nights all year round, and 75% of weekends between 11:00 and 15:00 when embedded generation suppresses system demand.
- **Scenario 2:** ***Reactive power service to manage a transmission voltage export constraint.*** The virtual power plant at each GSP will be instructed to produce reactive power. This service is driven by outages on the transmission system and by interconnector flows on the south coast. Therefore this instruction is not as frequent as Scenario 1. It is anticipated that the service would be instructed during times of peak system demand when interconnectors are flowing full power into the GB grid.
- **Scenario 3:** ***Active power service to manage a transmission thermal constraint***. The instruction for the virtual power plant will be to curtail active power to manage flows on the transmission system so they remain within acceptable asset short term ratings. The requirement for the service is driven by planned and unplanned transmission outages and existing and future interconnector flows and exports from the DNO network. An example of an instruction could be to curtail power from one GSP when export levels on the south coast exceed transmission asset short term ratings. This is not a frequent instruction.

8 Conclusions

This paper has presented an overview of the technical framework proposed in the Power Potential project for the coordinated control of transmission and distribution networks in Great Britain. This is the first trial of its kind in the world. It will enable distributed energy resources (DER) located in the distribution network to provide transmission support by offering dynamic voltage control from these resources. The aggregated response from DER will be considered as an equivalent virtual power plant (or SVC) at the transmission-distribution interface points. Simulation studies are included in the paper to validate the theoretical principles of the proposed DERMS control. The value of this new control option to the GB System Operator is also emphasised. It is anticipated that the Power Potential project will defer the need for network reinforcements, enable DER to participate and deliver market services and will facilitate DNO transition to the DSO (Distribution System Operator) business model. This would also allow increased renewable generation to be connected in the area, realising savings for UK consumers.

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