INTEGRATION OF DISTRIBUTED REACTIVE POWER SOURCES THROUGH VIRTUAL POWER PLANT TO PROVIDE VOLTAGE CONTROL TO TRANSMISSION NETWORK

Danny PUDJIANTO
Imperial College London – UK
d.pudjianto@imperial.ac.uk

Predrag DJAPIC
Imperial College London – UK
p.djapic@imperial.ac.uk

Goran STRBAC
Imperial College London – UK
g.strbac@imperial.ac.uk

Biljana STOJKOVSKA
National Grid ESO – UK
biljana.stojkovska@nationalgrid.co.uk

Inma MARTINEZ
National Grid ESO – UK
inma.martinez@nationalgrid.com

Ali R. AHMADI
UK Power Networks – UK
alireza.ahmadi@ukpowernetworks.co.uk

ABSTRACT

This paper describes the results of studies carried out as part of the on-going Network Innovation Competition (NIC) Power Potential project which is investigating the use of distributed energy resources (DER) to support voltage control on transmission network. In order to enable the use of DER for transmission services, a sequential two-stage reactive market approach and security constrained optimal power flows based reactive power allocation have been developed. It considers the dynamic availability and cost characteristics of virtual power plant (VPP) driven by changes in the local distribution system conditions in coordination with the state of the transmission network. A set of studies was carried out on the South East part of the GB transmission system to demonstrate the feasibility and effectiveness of the proposed methodology; the key findings from the analysis are presented and discussed in this paper.

INTRODUCTION

Operational flexibility will be at the core of facilitating a cost-effective evolution to a low-carbon electricity system [1]. Given the reduction in capacity of conventional fossil-fuel power generation, that historically was the key source of flexibility, evolving distributed energy resources (DER), including distributed generation (DG), distributed storage (DS) and demand-side response (DSR), connected to the distribution networks, will provide core flexibility services needed for real-time demand-supply balancing and management of congestion in transmission and distribution networks.

In this context, the Power Potential project [2] investigates the possible technical and commercial frameworks that will bridge the operational coordination challenges between the Great Britain electricity system operator (GB ESO) and distribution system operators (DSOs) in enabling access and use of DER and stimulating competition in the provision of reactive power support for transmission services from the local DER and transmission connected generators with the same level of playing field. The project investigates and trials the use of distributed reactive power sources to support the South East region of the GB transmission system which faces challenges in controlling voltages due to insufficient transmission reactive power sources to facilitate the growth of DER connections, and new interconnectors. Optimal utilisation of DER will delay/defer the need for investment in conventional technologies and transmission and distribution infrastructure.

In order to facilitate cost-effective system integration of DER, a new system operation paradigm and corresponding novel market design will be essential, and some radical changes are required:

- A shift from isolated operation of energy supply, transmission and distribution businesses towards a more integrated approach. The role of Distribution System Operator (DSO) also needs to evolve in order to facilitate the application to DER services not only for local distribution network management but also for the benefit to the national transmission system.
- Design of a new market that would maximise the overall economic value of DER considering both national and local objectives enabling DER to provide multiple services to different sectors of the electricity system. This can be achieved if DER has the opportunities to access various markets at the local level (e.g. congestion management of distribution networks) and national level (various forms of the reserve, capacity, reactive support, network management).

Operational challenges arise as the use of DER by different operators (i.e. DSOs and GB ESO) may trigger conflicts between serving the local or national objectives. Operational planning coordination will be required to maximise the synergy of using the distributed resources to provide multiple services. In order to maximise the access of DER for transmission, DSO may need to operate differently within the statutory limits as the current practices may impose a constraint on the usage of DER and hinder full access of DER to provide transmission services. For example, Pudjianto [3] demonstrated that sub-optimal voltage management might constrain the use of the DG capacity for providing frequency response or reserve services, especially during the low-demand period due to voltage limits. Improving voltage management by optimising the tap setting of distribution transformers can help relieve the ‘latent’ capacity of the DG so it can be used entirely to provide ancillary services needed by the system when needed.

In this context, the DSO will need to start optimizing their distribution system management not only for DSO’s objective but also to enable NETSO access to DER optimally considering distribution network constraints. The use of DER to serve the overall system objectives (both transmission and distribution) will lead to the optimal solution [4]. This issue has attracted many interests and been investigated in a number of reports by, e.g. EU SmartNet project [5], evolvDSO [6], and Energy Network Association in the UK [7].

MODELLING APPROACH

To enable the coordinated use of DER services to support distribution and transmission grids, a sequential two-stage market approach (Figure 1) has been developed and used in the Power Potential study to simulate some illustrative cases and analyse the feasibility and effectiveness of the concept.

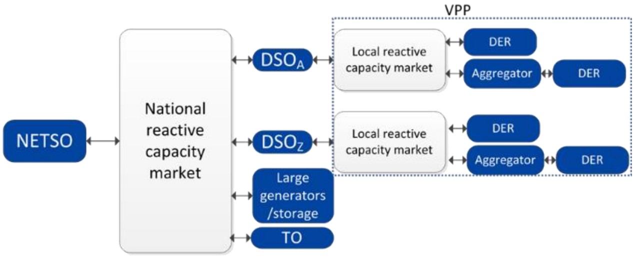

Figure 1 Provision of reactive power sources via local and national market

The sequential two-stage reactive market approach is described as follows:

1. The first step is to aggregate the technical and economic characteristics of the DER taking into consideration the distribution network constraints while optimising the network assets and control settings. This enables all distributed energy resources including the network assets to be presented as a large-scale transmission-connected generator which is fundamentally the concept of virtual power plant (VPP) [8]. Within the VPP area, DER will compete in a local energy market to provide their services to both the distribution and transmission system.
2. The second step involves the application of security constrained optimal power flow (SCOPF) algorithm [9] to identify the optimal portfolio of commercial contracts in the national reactive capacity market, of different durations, considering temporal changes in cost and capability of VPP (derived from the 1st step) in order to support secure transmission system operation. At present, traditional tools for selecting contract portfolio for voltage control of the transmission network are not capable of taking these effects into account. The services from VPP will compete with services from transmission-connected generators on a level playing field basis.

By using this approach, DER can participate both in the local market to provide services to local grids and in the national ancillary service, markets to provide services (voltage supports, frequency regulation and reserves) without violating local system limits.

The characterisation of VPP

DER connected to lower voltage networks and the local grid can be represented as a single large-scale power plant (VPP) connected at the respective transmission supply points. The characterisation process of the VPP is illustrated in Figure 2.

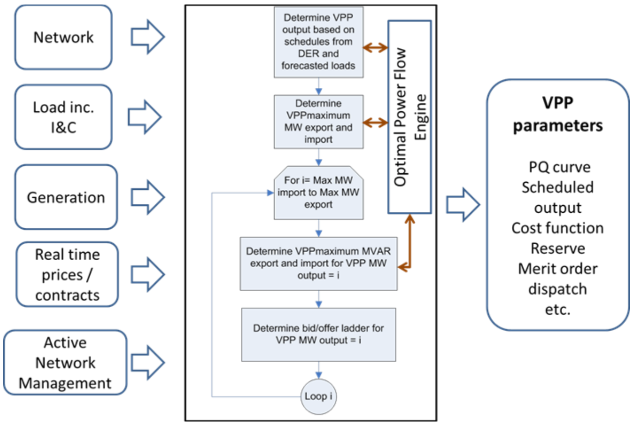

Figure 2 Characterisation process of VPP

For this process, the input data consist of network data (impedances, topology, ratings, transformers, reactive compensators), load data including the flexibility of controllable loads, generation data including power rating, reactive power capability and real-time prices or contracts for using the generators or flexible loads in the system balancing or constraint management. The scheduled generation outputs and the loads in the VPP area are then aggregated by the tool which calculates the scheduled power injection from the VPP using the Optimal Power Flow (OPF) formulation [8]. The OPF is also used to calculate the maximum MW export and import which satisfy all the operating constraints of the local network regarding voltage and flow limits. Once the spectrum of the MW output is identified, the range of reactive power output that can be exported or imported by the VPP area without violating operation constraints of the generators, loads and the network can be calculated. At the same time, the changes in generation cost due to the requirement to increase or decrease the output of VPP can be obtained. From those calculations, the VPP parameters can be synthesised. The parameters include the PQ technical capability curve, scheduled generation/load of the VPP, the VPP cost functions for both active and reactive power, the amount of reserve, and the merit order dispatch within the VPP.

SCOPF based reactive-power allocation

A multi-state SCOPF was developed to determine the optimal allocation and dispatch across all reactive power sources in the system in order to minimise the overall cost. This non-linear optimisation problem is described as follow:

$$\min \Psi = \sum_{g=1}^{G}\left(\pi_g^{Qc} \max\left(Q_{g,s}\right) + \sum_{s=1}^{S}\left(t_s\, \pi_g^{Qu}\, Q_{g,s}\right)\right) \quad (1)$$

Where π_g^{Qc}, π_g^{Qu} are the cost of contracting and utilising reactive power of generator/VPP g respectively; $Q_{g,s}$ is the reactive power output of generator/VPP g ; G and S are the set of generators/VPPs and operating scenarios respectively ; t_s is the duration (hours) of the operating scenario s.

The optimisation problem (1) is subject to power balance constraints and operating limits for voltages, power flows, generators/VPPs, transformers, and network reactive power compensators in all operating conditions considered in the study. The problem is solved using a non-linear optimisation solver from FICO[10].

CASE STUDIES

Based on the future generation scenario (year 2025) and network data provided by National Grid and UK Power Networks, the VPP models of distribution networks in the Power Potential areas with the grid supply points at Bolney, Ninfield, Sellindge, Canterbury North, and Richborough have been characterised. Generators and interconnectors were replaced by generic models. Due to the space limitation, only the reduced model of 132 kV and 33 kV distribution network in Bolney is presented in this paper (Figure 3). The total available capacity of DER in Bolney used in this study is 203.5 MW, 91 Mvar (lag and lead).

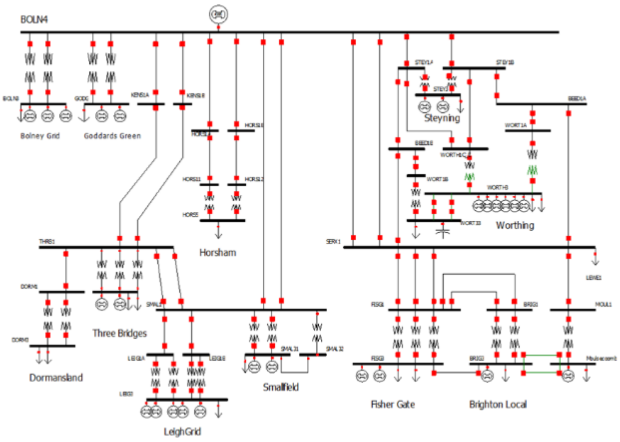

Figure 3 Distribution network diagram of Bolney

Figure 4 shows the cost function of reactive power services provided by Bolney VPP. The modelling results demonstrate that the VPP can provide 89 Mvar (lag) and 95 Mvar (lead) when tap changers and reactive compensators are not optimised. When they are optimised (Figure 5), a larger reactive capability, i.e.117 Mvar (lag) and 154 Mvar (lead), which is larger than the total reactive capability of DG, i.e. 91 Mvar (lag and lead), can be obtained.

It can be concluded that:

- There is the contribution of reactive power from the local distribution network assets. Smart operation, e.g. by optimising transformer taps could enhance the ability of reactive resources located in the distribution network to provide voltage support to the transmission system;
- There is no market barrier to access DG's reactive power capability in Bolney at the operating condition considered in this study, i.e. normal (intact) condition.

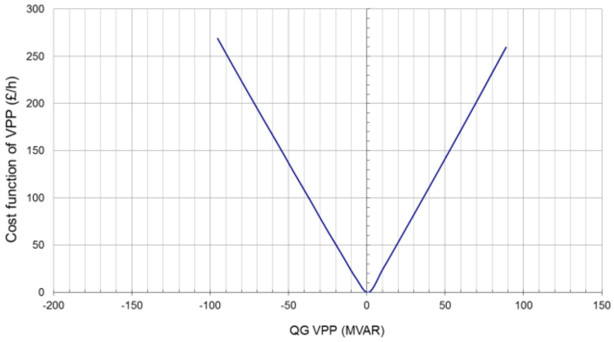

Figure 4 Reactive power cost function of Bolney VPP without optimising tap changers and reactive compensators

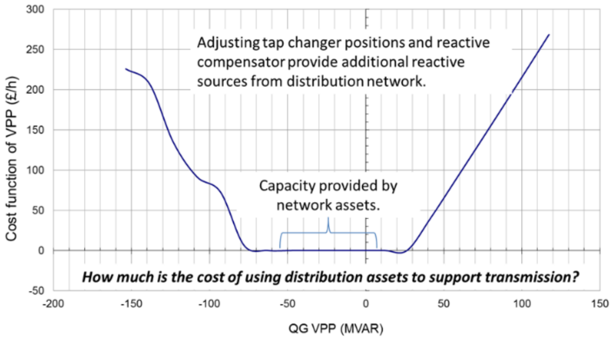

Figure 5 Reactive power cost function of Bolney VPP with optimised tap changers and reactive compensators

The results in Figure 5 suggest that between 75 Mvar (lag) and 25 Mvar (lead), the cost is zero since it is assumed that there is no cost of using distribution network assets to provide reactive injection/absorption at the GSP. Beyond that range, the VPP starts utilising resources from DER at £3/Mvarh (a pre-determined rate for the Obligatory Reactive Power Service [11]). The cost function for reactive power absorption is less linear than the one observed for reactive power injection; this may be caused by (i) the optimisation of voltages and reactive power control settings (transformers, and reactive compensators) which also affect (ii) losses and (iii) the numerical precision of the optimisation technique used in the characterising the VPP parameters. It is important to note that the cost function reflects the aggregated bids (utilisation) of reactive power services submitted by individual DER as it provides a price signal on the market value of reactive power services.

These results highlight the importance of having appropriate cost recovery mechanisms or incentives that should be in place to facilitate application of cost-effective measures, such as optimisation of transformer taps, or other active distribution network management measures that DSOs may take to enhance DERs access to providing services to the TSO. It may also be possible to temporarily overload distribution network assets (e.g. grid supply transformers or overhead lines) to enhance the provision of services from DERs to the transmission network.

VPP's capability is dynamic and changes according to local system conditions.

In contrast to a conventional generation, parameters of the VPP will vary depending on the system conditions following the changes in demand, generation availability, network topology and conditions, network control optimisation. For example, a circuit outage in Leigh Grid will reduce the reactive capability of the VPP to 145 Mvar (lead) and 95 Mvar (lag) as shown in Figure 6.

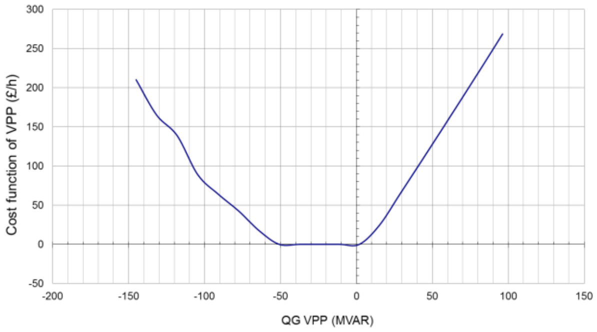

Figure 6 Reactive power cost function of Bolney VPP with a circuit outage

The outage also changes the reactive cost function slightly with distribution network assets providing less reactive capability (i.e. 50 Mvar(lead)).

Competitiveness of local VPP reactive power market

Enabling competition in the provision of ancillary services is vital to improve efficiency and minimise the cost of the services. As the distribution networks involved in the Power Potential (mostly at 132 kV and some 33 kV) are relatively strong, the networks do not impose any significant barriers for the DER to access and compete in reactive power markets. At a certain extent, this may also be contributed by the spatial distribution of the DER which tends to be clustered and connected to the low voltage of 132/33 kV substation.

Optimal allocation of reactive power contracts

Another set of studies has been carried out to investigate how the reactive power requirement may vary in different conditions considering intact and contingent system conditions. The studies use a set of credible contingencies (indicated by black circles in Figure 7) which are used to evaluate the capacity adequacy of the system including the sufficiency of the reactive power services.

For the intact and contingent conditions considered in the studies, the reactive requirement is calculated using the SCOPF. The results of the study using the summer peak operating conditions are shown in Figure 8.

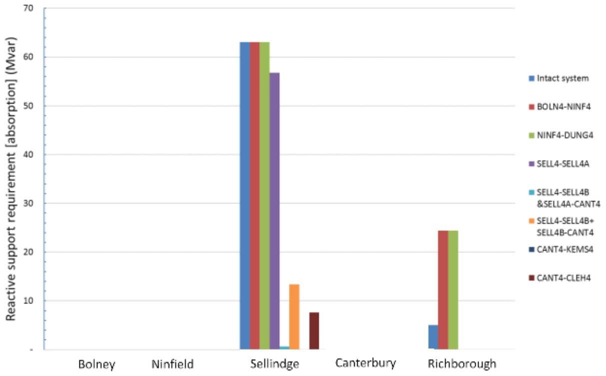

Figure 8 Reactive power requirement in different system conditions

The key findings analysed from the modelling results can be summarised as follows:

- Reactive power requirements are location specific; not all VPP are selected by the model.
- Reactive power requirements are system condition

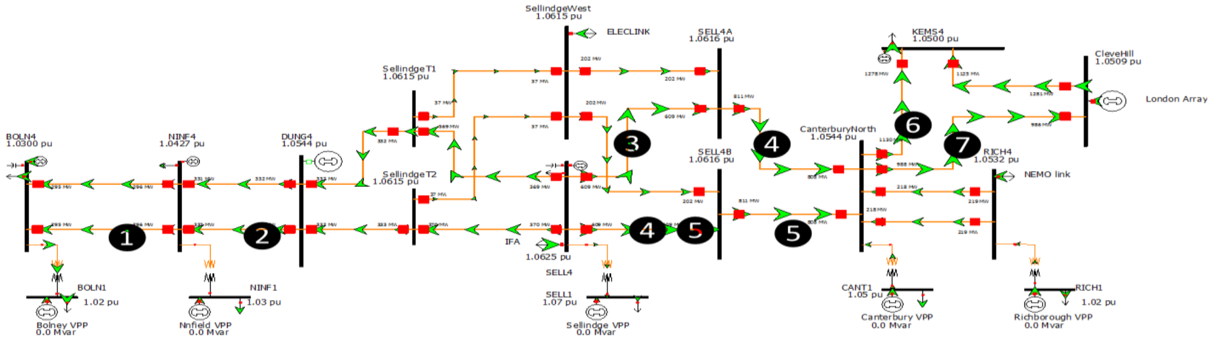

Figure 7 South-East GB transmission test system

specific. The different volume of reactive power services is needed in a different location depending on the system condition. Different contingencies are likely to trigger different reactive requirements.

- In general, contingent conditions require more reactive requirement than in the intact system. This is not surprising given that a circuit outage tends to increase the system impedance and amplify the voltage problems in the system. This may have an implication on how the reactive power services should be remunerated, e.g. to use both availability and utilisation payment in the market rather than having only the utilisation payment.

Another study uses the winter peak condition where the system loading is relatively high coincide with low DER output and no import from the interconnectors. This condition results in low voltage problem across the test system; notably, the voltage at Richborough (the end of long transmission corridor) is at the lower limit. As all the reactive requirement can be provided by VPP Richborough, the contracted capacity to deal with all (intact and contingent) conditions is the maximum reactive requirement (118 Mvar [lag]) across those conditions. This again shows the locational value of reactive power. The contractual reactive capacity requirement across different period can be summarized in Table 1.

Table 1 Reactive allocation for different contracting periods

In Mvar	Sellindge VPP	Richborough VPP
Summer	-62	-24
Winter	0	+118
Year round	-62	- 24 and +118

While the participation of DER can increase the number of market participants and improve the competition across the service providers, the locational value of reactive power can create market power; this issue will be addressed in our future work.

CONCLUSION

The studies demonstrate the feasibility of the sequential reactive power market framework using the VPP approach to aggregate DER capacity and local distribution network characteristics to enable access of reactive power markets to DER. The value of the reactive power of VPP varies with time, location, demand and system conditions. DER can provide reactive sources more effectively as it can be closer electrically to the part of the system that needs support compared to large-scale transmission connected generators. This requires the role and responsibility of DSO to evolve to optimise the distribution network and facilitate optimal access for DER to provide transmission services. Distribution network assets can also provide reactive power support to transmission, and this requires the development of a commercial framework that can remunerate the services from distribution assets. The reactive capability of VPP is dynamic and changes according to local conditions in the distribution network, and therefore, in order to measure the real-time capability of the VPP, it requires real-time monitoring and active management of the resources. The proliferation of Distributed Energy Resource Management Systems (DERMS) and Active Network Management (ANM) systems on DNO networks where all the network data, schedules and information are available, provides the infrastructure to effectively optimise the distribution network and provide services to GB ESO in a coordinated fashion [12].

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