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Virtual power plant: managing synergies and conflicts between transmission system operator and distribution system operator control objectives

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Abstract: In this study, the implementation of virtual power plant (VPP) as a means to coordinate the use of distributed resources for different control objectives by transmission system operator and distribution system operator is described. In order to illustrate the concept, a range of illustrative studies demonstrating the application of VPP concept on a real 11 kV system in Brixton will be presented, using data from the Low Carbon London project. The studies demonstrate the changes in the operating characteristics of the VPP area over a range of system operating conditions.

1 Introduction

As the UK energy system evolves in its transition to a low-carbon energy system, the flexibility of the power system which is traditionally provided by fossil-fuel based power generation is expected to decrease along with the reduction in the use and capacity of those conventional plants. Evolving non-network technologies connected to distribution networks such as distributed energy resources (DERs), which include distributed generation (DG), distributed storage and demand side response (DSR), could provide flexibility services to support real-time balancing, national and/or local network congestion management, and reduce the need for investment in new generation, transmission and distribution capacity.

However, the use of DER for different objectives may trigger conflicts. For example, increasing the output of DG/storage to balance the national system by transmission system operator (TSO) may trigger voltage or reverse power flow problems at local distribution, especially during low demand periods. Conversely, the use of DER to reduce the local peak demand to avoid local constraints by distribution system operator (DSO) may increase loading at the transmission. This indicates that coordination will be required in order to use the distributed resources to provide multiple services for different objectives. The fact that the energy supply sector and energy transport sectors (distribution and transmission networks) are operated by different commercial organisations with the limited level of integration and coordination such as in the UK and some other countries may become a barrier for utilising fully the potential of flexibility services provided by distributed resources.

Virtual power plant (VPP) described in [1] is a primary option for facilitating closer and active interaction between TSO and DSO in order to access and control distributed resources. The VPP enables more active TSO/DSO interaction and facilitates a shift from isolated operation of energy supply, transmission and distribution businesses towards a more integrated (whole system) approach. DSO would have an active role in informing the TSO regarding the controllable VPP capability and would offer access to VPP operators to distribution networks. The TSO then could use the VPP as resources to manage the congestion in the national transmission system and for system balancing to improve the utilisation of low carbon technology assets and renewable energy. Through the VPP concept, the overall potential and economic value of DER could be maximised considering both national and local objectives.

This paper is structured as follows. First, the concept of VPP as an option for defining the role of DSO in supporting energy market operation and system management is described. Second, the method to calculate the operating and cost characteristics of the VPP is described. Third, in order to illustrate the concept, a range of illustrative studies demonstrating the application of VPP concept on an 11 kV system in Brixton will be presented, using data from the Low Carbon London (LCL) project led by UK Power Networks. It is important to note that unlike traditional generators, the technical and cost characteristics of VPP vary in time following the changes in the availability of resources and system conditions. Finally, a conclusion is given at the end of this paper.

2 DSO in supporting energy market operation and system management

In the future highly distributed system with active demand side, the interaction between TSO and DSO will develop further, and adapt to support the new system. This new system will be characterised by

- Active management of distribution network.
- Balancing (and system management) at distribution level as well as transmission.
- The inclusion of the real-time impact of the distribution network on generation output (e.g. constraints, losses, and topology) in system operation and management.

Given this, the system management responsibilities seen at TSO level will be devolved down to DSO level. The future highly distributed system will require more system management services at the distribution level, and thus the technical-based VPP (TVPP) comes into play more strongly, and the interactions between the commercial-based VPP (CVPP) and DSO (with a TVPP) strengthen.

The interactions between different activities as presented in Fig. 1 are described below:

(i) DER (from different locations) contract with an energy supplier (or balancing responsible party) to become part of a CVPP portfolio.

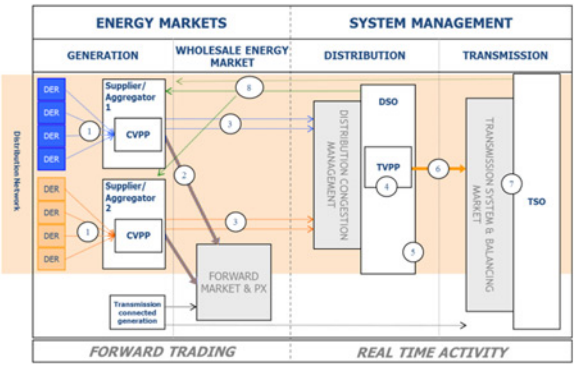


Fig. 1 *DSO role in supporting interaction of energy market and system management*

(ii) The supplier optimises the position of its CVPP portfolio in the wholesale energy markets. Optimisation algorithms in [2, 3] can be used for this purpose.
(iii) At gate closure, the supplier optimises the position of the DER in its CVPP portfolio by offering DER capabilities to the DSO (for local system management and inclusion in the TVPP), note that to offer location-specific services bids and offers from single DER or smaller aggregated groups of DER are submitted.
(iv) The DSO aggregates market prices from DER in a network area with local network data, this forms a TVPP.
(v) The DSO optimises the distribution network operation and manages local network constraints by calling on services the TVPP.
(vi) After balancing the local system the DSO, the aggregated TVPP output shows the characteristics of the entire local network at the transmission grid supply point. This characterisation can also include potential for provision of scheduled ancillary services to the TSO (provided through a bilateral agreement between the TSO and the TVPP operator).
(vii) The TSO evaluates the TVPP offerings along with bids and offers from transmission connected generation and other TVPP portfolios.
(viii) DSO contacts the CVPP operator to dispatch their resources in an efficient manner according to the accepted bids or offers by the TSO.

The following section describes how the technical and cost characteristics of aggregated resources and network constraints can be identified.

3 Methodology

The Imperial's VPP tool builds a set of VPP parameters, i.e. similar to large-scale conventional generator data and its cost function of delivering energy and system services. By using this approach, a large number of DSR resources connected in lower voltage networks can be represented as a single large-scale power plant connected at the respective transmission supply points. The outline of the aggregation process carried out by the tool is illustrated in Fig. 2. The process determines the characteristics of VPP taking into account local network constraints which ensure that the delivery of the energy output or system services from the VPP will not be constrained by the local system.

The input data of the tool comprises network data (impedances, topology, ratings), load data including the flexibility of controllable loads (industrial, commercial, and residential), generation data (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 formulation. The tool also calculates the maximum MW export and import which satisfy all the operating constraints of the local network in terms of voltage and flow limits. Once the spectrum of the MW output is identified, the tool calculates 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. At the same time, the tool also calculates the changes in generation cost due to the requirement to increase or decrease the output of VPP.

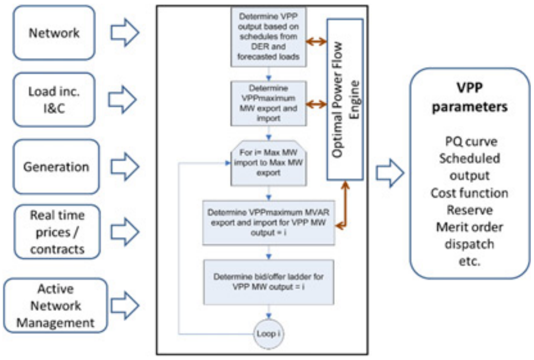


Fig. 2 *Outline of the process to derive VPP parameters*

From those calculations, the VPP parameters can be obtained. The parameters include the PQ curve and scheduled generation/load of the VPP, the VPP cost function, the amount of reserve, and the merit order dispatch.

4 Case studies

Fig. 3 shows the diagram of the part of Brixton 11 kV network which was used to demonstrate the applications of the VPP in the LCL project. Two 11 kV feeders are modelled in detail, i.e. SE_1 and SE_3. Feeder SE_3 is one of the Engineering Instrumentation Zones in the LCL project. In the normal intact condition, these two feeders are not connected but in a contingency situation, these two feeders can be connected by closing the Normally Open Point which energises the line between substation 91,043 and substation 91,045.

As shown in Fig. 3, Feeder SE_1 and SE_3 are supplied by 2 × 22.5 MVA transformers. The loads and generation in other feeders which connect to those transformers but not modelled in detail are aggregated as loads. The total load used in this study was 22.1 MW and 7.27 MVAr which corresponded to the peak load of this network according to the measurement.

For the purpose of this study, a set of CHP generators and Industrial and Commercial (I&C) loads has been added to the

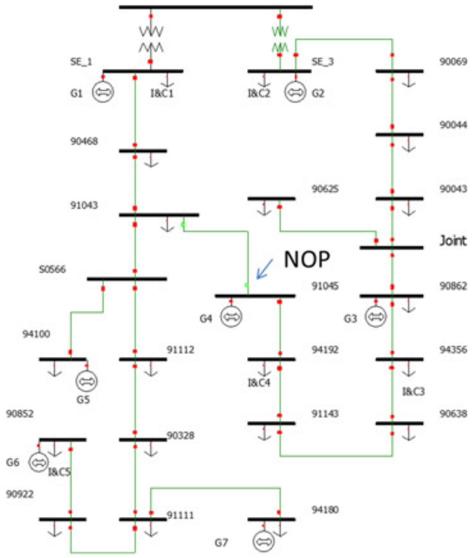


Fig. 3 *Test system*

Table 1 Generation and I&C data

Bus name	Type	Scheduled output, MW	P_{cap} installed, MW	Q_{min}, MVAr	Q_{max}, MVAr	Offers *int, E/MWh	Bits *Der, E/MWh
SE_1	G1	2.10	2.50	−1.55	1.55	85.0	17.5
SE_3	G2	0.00	5.00	−3.10	3.10	80.0	10.0
90,862	G3	1.60	2.00	−1.24	1.24	50.0	12.0
91,045	G4	2.80	3.50	−2.17	2.17	55.0	15.0
94,100	G5	0.00	1.50	−0.93	0.93	70.0	10.0
90,852	G6	0.00	4.00	−2.48	2.48	75.0	10.0
94,180	G7	2.40	3.00	−1.86	1.86	45.0	10.0
SE_1	I&C1	0.00	1.68	−0.55	0.55	60.0	−100.0
SE_3	I&C2	0.00	1.84	−0.60	0.60	65.0	−110.0
94,356	I&C3	0.00	0.07	−0.02	0.02	90.0	−120.0
94,192	I&C4	0.00	0.09	−0.03	0.03	95.0	−130.0
90,852	I&C5	0.00	0.10	−0.03	0.03	100.00	−140.0

network. In this study, the balancing sources are not only provided by generators but also by I&C loads. The total installed MW capacity of the generators in this study is 21.5 MW and the flexible capacity of the I&C loads is assumed to be around 20% of the total I&C loads. All generators and I&C loads have the capability to operate with 0.95 power factor. The capacity, scheduled output, operating limits and a bid-offer cost function of each generator are shown in Table 1. In this study, some CHP generators have been scheduled to produce electricity. The total scheduled output of generators and I&C loads is 8.90 MW.

Fig. 4 shows the *PQ* curve of the VPP Brixton. In this case, the reactive capability of the VPP Brixton for a different MW output is slightly different. However, there is a possibility that the reactive capability could be significantly different and therefore deriving the *PQ* capability is important in order to characterise the VPP parameters.

The output of the VPP is modulated by changing the dispatch of the generators and I&C loads in the VPP area. The changes in the dispatch have to be carried out economically and the most economic resources have to be used first as much as possible while respecting the network operating constraints.

Fig. 5 shows the required changes in the DG output and I&C loads to modulate the VPP output. For example, to increase the VPP output to 2 MW, the output of G7, G3 and G4 need to increase by 0.6, 0.4 and 0.7 MW respectively. Furthermore, the I&C_SE1 needs to reduce its load by 0.2 MW. G7, G3 and G4 are the generators with the lowest (offer) prices and therefore it is expected that these generators are first to be used.

If the operator wants to reduce the VPP output to −5.4 MW, the output of G1, G4 and G3 need to be reduced by 2.1, 2.8 and 0.51 MW, respectively. Since G1, G4 and G3 are the generators which are willing to pay the highest (bid) prices to reduce their output, therefore, it is expected that these generators are first to be used to reduce the VPP output. This demonstrates that the use of resources in the VPP area has been carried out in an efficient economic manner.

The cost of modulating the output of the VPP is also calculated by the tool. The cost function of the VPP is presented in Fig. 6. The cost reflects the cost asked by the resources in the VPP area to change the output of their power generation or to change their loads. The cost may be negative as illustrated in the figure below, for example when the output of VPP is between 0 and −10 MW. In this case, the generators are willing to pay the market operator to reduce their output below their operating cost for generating the electricity; however, as the generators produce the electricity to supply their consumers, the reduction in their output has to be substituted by the increase in the output of other generators in order to maintain the balance between supply and demand. Eventually, this increases the system operating cost.

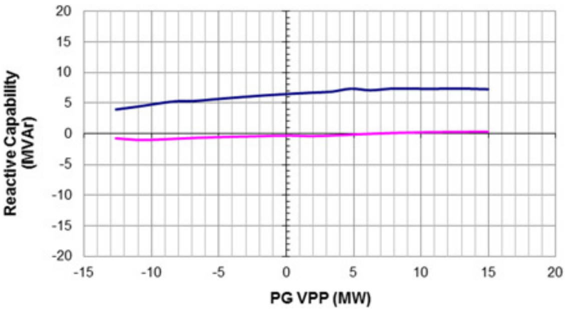
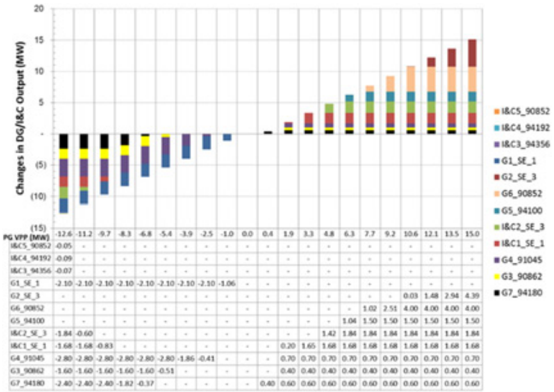


Fig. 4 *VPP's PQ characteristic*



PG VPP (MW)	-12.6	-11.2	-9.7	-8.3	-6.8	-5.4	-3.9	-2.5	-1.0	0.0	0.4	1.9	3.3	4.8	6.3	7.7	9.2	10.6	12.1	13.5	15.0
I&C5_90852	-0.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I&C4_94192	-0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I&C3_94356	-0.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G1_SE_1	-2.10	-2.10	-2.10	-2.10	-2.10	-2.10	-2.10	-2.10	-1.06	-	-	-	-	-	-	-	-	-	-	-	-
G2_SE_3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	1.48	2.94	4.39
G6_90852	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.02	2.51	4.00	4.00	4.00	4.00
G5_94100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.04	1.50	1.50	1.50	1.50	1.50	1.50
I&C2_SE_3	-1.84	-0.60	-	-	-	-	-	-	-	-	-	-	-	1.42	1.84	1.84	1.84	1.84	1.84	1.84	1.84
I&C1_SE_1	-1.68	-1.68	-0.83	-	-	-	-	-	-	-	-	0.20	1.65	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68
G4_91045	-2.80	-2.80	-2.80	-2.80	-2.80	-2.80	-1.86	-0.41	-	-	-	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
G3_90862	-1.60	-1.60	-1.60	-1.60	-1.60	-0.51	-	-	-	-	-	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
G7_94180	-2.40	-2.40	-2.40	-1.82	-0.37	-	-	-	-	-	0.40	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60

Fig. 5 *Internal VPP merit order dispatch characteristic*

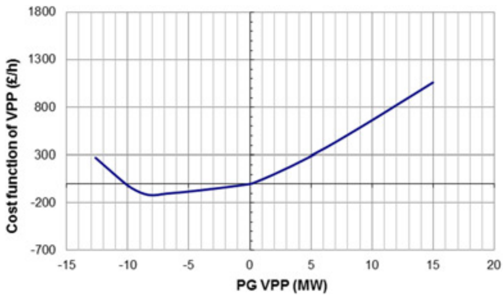


Fig. 6 *Cost function of the VPP*

As shown in Fig. 6, the cost of the VPP is positive when the output of the VPP is positive or below −10 MW. In this case, generators and I&C loads will ask payment to modulate their electricity production or load. The national system operator and the relevant distribution system operator can use such information to determine in an optimal economic manner whether and by how much they would like to dispatch the VPP generator in order to manage the constraints and/or to balance the system.

It is important to note that the usage of the resources in the VPP area by the national or distribution system operator should not cause operating constraint violation in the VPP area. As the national (or distribution) system operator is likely not to model the network of the VPP area, they cannot assess the impact of the usage of the VPP resources on the VPP network and therefore rely on the information from the VPP operator. The VPP operator must ensure that the parameters of the VPP are derived taking into account local network constraints.

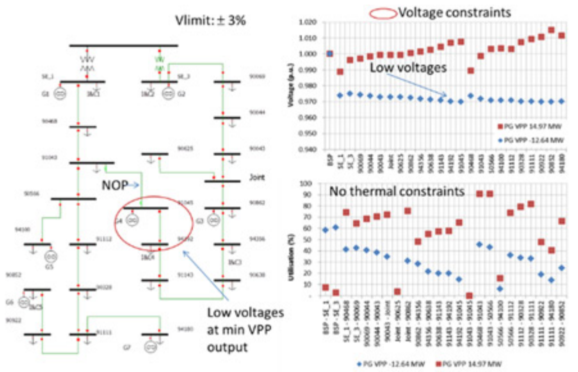


Fig. 7 *Internal VPP merit order dispatch characteristic*

The voltage at each node and the utilisation of each circuit in the conditions where the VPP output is at maximum and minimum are presented in Fig. 7 (right diagrams). The operating voltage limit assumed in this study is ±3%. In both conditions the voltages and the utilisation levels are within the statutory limits.

The loading of the VPP area is at a maximum where the VPP output was at −11.41 MW. In this situation, it was expected that the voltage would drop along the feeder. The right upper diagram of Fig. 7 shows that at buses 94,192 and 91,045 which are at the end of the SE_3 feeder, the voltages are at the minimum limit. Similarly, the voltages along SE_1 feeder are also at the lower limit.

At the maximum VPP output, all generators produce electricity at maximum and I&C reduce their loads. In this condition, it is expected to see the voltage rise effect as shown in Fig. 7. Voltages at the end of the feeder farthest from the supply substation, e.g. voltage at the buses 91,045 and 90,852 are the highest but the values are still within the 3% limit. In both conditions, the utilisation of all circuits is below 100%. This is shown in the right lower diagram of Fig. 7.

4.1 Impact of tap-changing optimisation on the VPP

In the second study, the VPP parameters are recalculated following the optimisation of the OLTC's setting at the 33/11 kV substation. The impact on the *PQ* curve of the VPP is shown in Fig. 8.

4.2 Impact of network re-configuration on the VPP

In the third study, the VPP parameters are recalculated following the network reconfiguration in the VPP area due to the fault at SE_1 supply transformer. Due to the fault, feeder SE_1 is supplied from the SE_3 feeder by activating the circuit connected buses 91,043 and 91,045. The comparison between the VPP parameters in the intact system (first case) and the parameters after the network reconfiguration (second case) following the fault at SE_1 supply transformer is presented in Fig. 9.

After network reconfiguration, the capability of the VPP to increase its load reduces significantly from 12.64 MW in the intact system to 2.34 MW. The reactive capability of the VPP also decreases, for example, the maximum reactive power injection ($Q_{\max}$) decreases from 7.33 to 2.30 MVAr. However, the capability of absorbing reactive power increases slightly from 1.04 to 2.18 MVAr. The impact on the reactive capability of the VPP also changes the scheduled reactive power load of the VPP from 6.29 to 1.31 MVAr while keeping almost the same MW load.

It is important to note that the network re-configuration also affects the cost parameters of the VPP, but due to the space constraint, it cannot be shown here. This demonstrates that the VPP's parameters are dynamic depending on the temporal system conditions, availability of resources, and other factors such as costs, network control capability and so on.

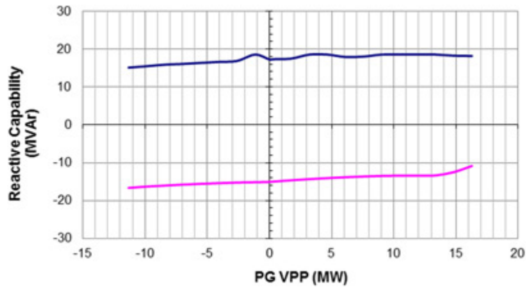


Fig. 8 *Impact of OLTC optimisation on the VPP*

By optimizing the OLTC, a higher reactive capability can be obtained. This can be used to support the reactive and voltage management at the higher voltage level.

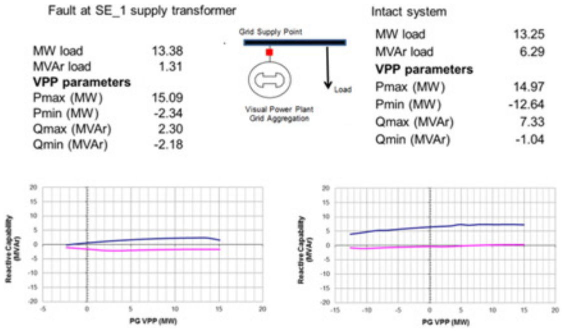


Fig. 9 *Changes of VPP parameters due to fault-driven network re-configuration*

5 Conclusions

The results of the studies demonstrate the following:

- Active and reactive power capabilities of the VPP are affected by the dynamic changes in the operating conditions of the VPP area and the level of temporal local constraints.
- The use of VPP resources within the VPP operating capability will not violate the local network constraints and therefore it prevents conflict between different VPP applications, for example for local network management and system balancing.
- The use of resources within the VPP area is carried out in an efficient economic manner.

It can be concluded that the VPP concept enables closer interaction between TSO and DSO and supports the integration of the whole system in managing the synergies and conflicts between distribution network, energy supply, transmission network objectives when allocating DER flexibility, which is key for optimal development of the system with high penetration of DER as a whole.

6 Acknowledgments

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