Use of Distributed Generation to Control Reactive Power at the Transmission Distribution Interface

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***Abstract*—There is an increasing interest in obtaining reactive power services for the transmission system from distributed energy resources. This involves coordination between the transmission and distribution companies, and the distributed generators. This paper presents a methodology to quantify the extent of reactive power provided by distributed generators to the reactive power seen at the transmission and distribution interface. Two case studies using computer load flow simulations are presented based on a real-world network. Results showed that when the distributed generators connected to the distribution network absorb reactive power there will be a multiplier of around 110% in the reactive power drawn from the transmission system. Similarly, if the distributed generators export reactive power the multiplier is around 90%. This study shows that there is a potential for providing reactive power support from distribution networks to the transmission system at the expense of additional active power losses in the distribution system.**

Keywords—reactive power, distributed generation, transmission, distribution network.

I. PROBLEM OF REACTIVE POWER IN THE GREAT BRITIAN TRANMISSION SYSTEM

The flow of reactive power (Q) controls the voltage of a transmission system by its interaction with the reactance of the high voltage circuits. Traditionally, large synchronous generators provided voltage control at transmission level by modifying their reactive power output. Capacitors, reactors, static Var compensators (SVCs) and static compensators (Statcoms) are also used. However, conventional generators connected to the transmission network are being replaced by distributed generation, leading to a lack of controllable reactive power sources in the transmission network. At present around 25% of GB electrical energy does not flow through the transmission system and this fraction is increasing.

The increase in DG, as well as increased installation of underground cables and extensive use of load equipment with limited inductive or even capacitive power factor has contributed to declining reactive power demand seen by the GB Electricity System Operator (ESO) [1]. The declining Active power/Reactive power (P/Q) ratio at some Grid Supply Points (GSPs) was discussed in [1]. As a consequence, there can be high voltages on lightly loaded transmission circuits especially at night. During 2017-18 there were three high voltage excursions and during 2018-19 there were two high voltage excursions reported within the National Transmission System [2].

A special case was reported on Saturday, 23rd May 2020 over the bank holiday weekend when the demand was unusually low at 23GW due to the combined impact of COVID-19 pandemic and the low bank holiday demand. It was sunny and windy which meant there was a high renewable generation output, much of it embedded. Similar conditions of lightly loaded circuits resulted in higher voltage profile during the pandemic in general. Therefore, additional generation services and wider network re-configurations were used to control voltages [3].

A conventional countermeasure to high transmission voltages in transmission networks is to absorb the excess reactive power by installing static compensation elements such as shunt inductors, SVCs or Statcoms. However, these solutions require capital expenditure and there may be the potential to provide reactive power control, at least in the short term, from distribution networks to the transmission system [4]. In [5], it was argued that the strategy of using many, small, distributed Static Var Systems (SVS) located at distribution busbars is more attractive than a few large bulk SVCs located at transmission busbars. In [6], tap staggering was discussed as a way of absorbing reactive power. In [7], successive optimal reactive power flow simulations were used for the assessment of reactive power flexibility between medium and high voltage networks. The power factor of distribution connected generators, as well as the tap positions of GSP transformers were controlled to minimise voltage deviations. In [8], a 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 is presented.

However, there has been no general consensus that reactive power support to the transmission system should be provided from the distribution system. Reasons for this could be the conflicts of objectives between distribution and transmission network operators. Distribution system operators are interested in operating the network with minimum real power losses. High reactive power flow causes additional current flows in the distribution network and leads to additional power losses and possible voltage excursions. Also, there are no established methods of quantifying the effectiveness of reactive power flows in distribution circuits at the transmission/distribution.

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This paper presents two (heuristic) case studies to investigate the possibility of using distribution connected gas fired reciprocating synchronous generator sets to provide reactive power support to the transmission system. The technical feasibility of this idea is assessed using computer load flow simulations. A methodology for calculating the sensitivity of providing reactive power from the generators to the reactive power seen at transmission/distribution interface is developed. It was shown that, in these examples, the reactive power at the transmission/distribution interface varied between 90-110% of that produced/absorbed by the generators.

II. Methodology

A. Description of case studies

A model of part of the South Wales network is used for this study. Network data was obtained from the Western Power Distribution's (WPD) Long Term Development Statement (LTDS) for the year 2018. The network model consists of voltage levels from 400kV down to the distribution level 11kV. Two simplified network models were developed on the IPSA (Interactive Power System Analysis) software platform considering generators providing power to;

i. one grid supply point (GSP), Fig. 1.
ii. multiple GSPs through interconnected 132 kV circuits, Fig. 2.

Maximum load and the power factor (*pf*) of the load at each busbar, transformer impedances, transformer minimum and maximum tap positions, and distribution and transmission line impedances were obtained from WPD's LTDS. Minimum load was assumed to be 25% of the maximum load. The total maximum load of the network connected to only 1 GSP was 226 MW and 7 MVars. The total maximum load of the network connected to 3 GSPs was 605MW and 43MVars.

Three reciprocating gas fired generation plants each with eight 2.48MVA generators (approximately 20 MVA), are connected at 11 kV. These generators can operate at either leading or lagging power factor (can export or import reactive power). The specifications of the gas fired generators and the technical parameters of the three 11kV/33kV transformers (each with 18MVA rating) at the gas fired generation plants were obtained from Welsh Power.

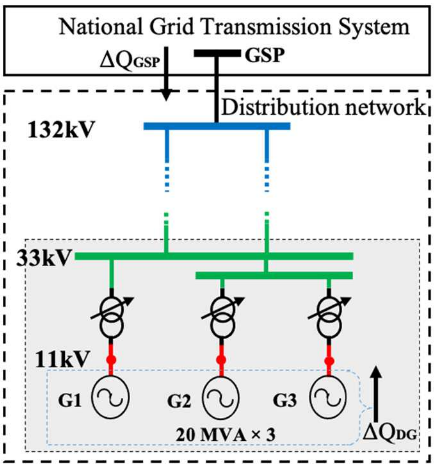

Fig. 1. A reduced representation of the simplified network with 1 GSP.

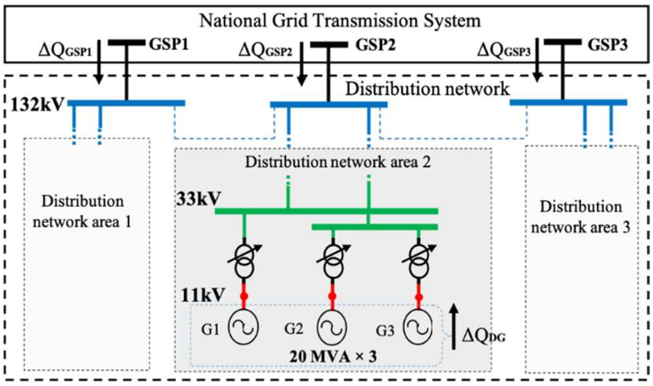

Fig. 2. A reduced representation of the simplified network with multiple GSPs connecting in parallel at 132kV level.

Power flow simulations of the two networks were conducted for the following cases, with:

i. no distributed generation,
ii. the gas fired generators operating at leading and lagging power factors,
iii. minimum and maximum network load, and
iv. varying power factors (*pf*) of network loads.

The change in reactive power at the GSPs (ΔQ_{GSP}) was compared to the change in the reactive power originating from the gas fired generation plants (ΔQ_{DG}) at 11kV. Real and reactive power losses of the networks were obtained for the different cases.

B. Calculation of Q-senstitity at transmission level

The effect of reactive power injected or absorbed by the DG is calculated compared to a reference case when the DG injects 48 MW of active power (P_{DG}) at unity power factor (i.e. fulfilling their primary function of frequency support).

Reactive power flows seen at the GSPs in the reference cases ($Q_{GSPreference}$) are compared with when the distributed generation inject or absorb reactive power ($Q_{GSPstudy}$). Then the Q-sensitivity of a selected study is calculated as shown in (1). Q_{DG} is the amount of reactive power injected or absorbed by the DGs.

$$Q - sensitivity = \frac{(Q_{GSPreference} - Q_{GSPstudy})}{Q_{DG}} \times 100\% \qquad (1)$$

The following example of the network connected to 1 GSP is used to illustrate the principal factors affecting Q-sensitivity.

In the reference case (Fig. 3), the DGs collectively inject only active power (+48MW) and the network load is at the minimum (25% of maximum load). The active and reactive power flows seen at the GSP are +9.15 MW and +7.26 MVars, in the direction of the arrow (ΔQ_{GSP}).

In Fig. 4, the DGs collectively inject 48 MW of active power and absorbs 23.7 MVars of reactive power to and from the network. The network load is same as in the network in Fig. 3. The active and reactive power flows seen at the GSP have now changed to +9.42 MW and +34.02 MVars, in the direction of the arrows. Hence the Q-sensitivity of DGs for the case in Fig. 4 is calculated as follows (using (1)),

$$Q - sensitivity = \frac{(Q_{GSPreference} - Q_{GSPstudy})}{Q_{DG}} \times 100\%$$

$$= \frac{7.26MVar - (+34.02MVars)}{23.7MVars} \times 100\%$$

$$= 112.91\%$$

Around 13% more reactive power flow from the transmission network than is absorbed by the generators.

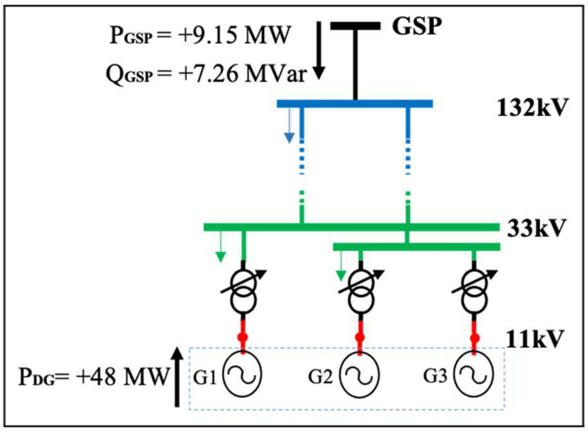

Fig. 3. Illustration of real and reactive power flows at transmission level; the reference case when the DGs export only active power.

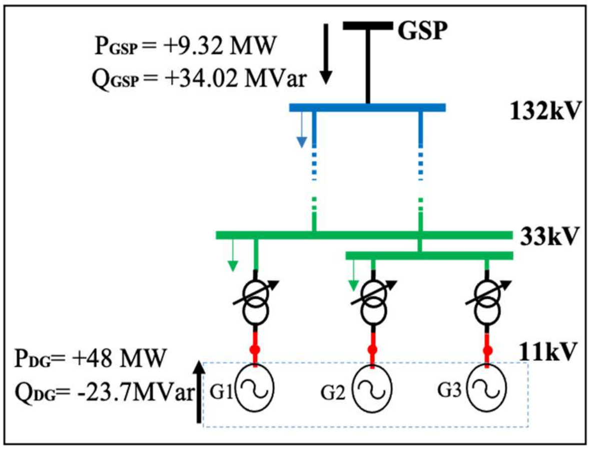

Fig. 4. Illustration of Q-sensitivity at transmission level; the case where DGs exporting active and absorb reactive power.

III. Results

A. Simulation results of the case with 1 GSP

TABLE I. shows the Q-sensitivity and active power losses (P losses) of the network when the DGs are exporting and absorbing reactive power, at minimum and maximum network load. Reactive power losses (Q losses) are also recorded. TABLE I. shows that, when the distributed generation exports reactive power the Q-sensitivity is around 90%. Similarly, if the generation absorbs reactive power there will be a Q-sensitivity of around 110%. There has been a considerable increase in P losses (increase of between 25% to 45%) compared to the reference case. It is noticeable that, at minimum load P losses with DGs at all the operating modes are considerably higher than the cases with no DGs.

If the *pf* of the network loads change, then the Q-sensitivity changes slightly as shown in Fig. 5. Fig. 6 shows the percentage of the change in P loss with varying *pf* of network loads. The power flow simulations did not converge for two cases; (i) when network load is at maximum, *pf*=-0.9 (i.e. highly capacitive load) and the generators export reactive power (ii) when network load is at minimum, *pf*=+0.9 (i.e. highly inductive load) and generators export reactive power.

Fig. 6 shows that, all the simulated cases have seen an increase of P losses. There is an increasing trend of P losses when the *pf* of network load changes from capacitive to inductive and if the DG absorbs reactive power. In contrast, there is a decreasing trend of the P losses when the *pf* of network load changes from capacitive to inductive if the DG exports reactive power. In both Fig. 5 and Fig. 6, the sign of *pf* is positive for inductive load and negative for capacitive load. The tap changers of the distribution network were modelled, and no voltage excursions were recorded for all the simulation studies.

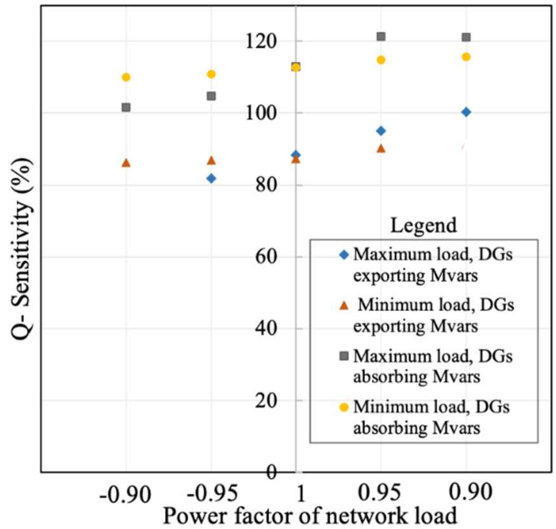

Fig. 5. Change in Q-sensitivity with varying power factors (pf) of network load for the case with 1 GSP.

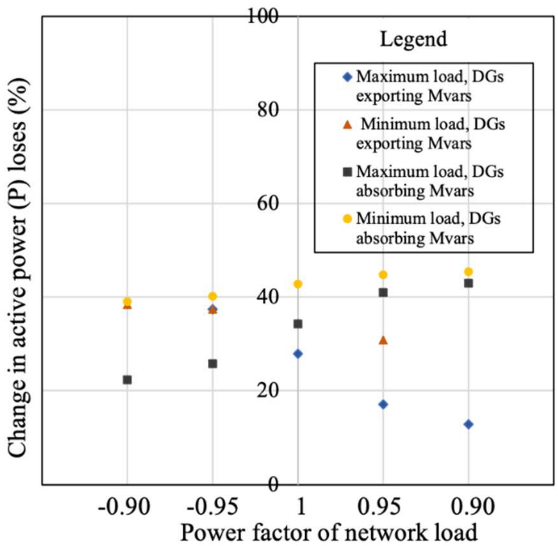

Fig. 6. Percentage of change in P losses against the reference case, with varying power factors of network load for the case with 1 GSP.

TABLE I. SIMULATION RESULTS OF THE NETWORK WITH 1 GSP (*PF* OF THE LOADS ARE AS IN WPD'S LTDS.

Network load	DG operation	P_{GSP} (MW)	Q_{GSP} (MVar)	Q-sensitivity (%)	Losses		Increase in PLoss (%) compared to the reference case
					PLoss (MW)	*QLoss (MVar)*	
Minimum	No DG	56.55	0.614	-	0.029	1.144	-
	DGs export 48 MW (reference case)	9.15	7.26	-	0.622	5.506	-
	DGs export 48 MW & 35.7 MVars	9.36	-24.41	88.71	0.836	9.533	34.40
	DGs export 48 MW & absorb 23.7 MVars	9.42	34.02	112.91	0.892	8.561	43.40
Maximum	No DG	226.55	26.29	-	0.461	19.267	-
	DGs export 48 MW (reference case)	178.87	24.56	-	0.781	17.526	-
	DGs export 48 MW & 35.7 MVars	179.08	-7.19	88.94	0.991	21.476	26.89
	DGs export 48 MW & absorb 23.7 MVars	179.15	51.46	113.50	1.054	20.732	34.96

TABLE II. SIMULATION RESULTS OF THE NETWORK WITH MULTIPLE GSPS (*PF* OF THE LOADS ARE AS IN WPD'S LTDS).

Network load	DG operation	Q-sensitivity (%)			Q-sensitivity (%) GSP1+GSP2+GSP3	Losses		Increase in P_{Loss} (%) compared to the reference case
		GSP1	*GSP2*	*GSP3*		*P_{Loss} (MW)*	*Q_{Loss} (MVar)*	
Minimum	No DG	-	-	-	-	0.127	20.024	-
	DGs export 48 MW	-	-	-	-	0.634	24.616	-
	DGs export 48 MW & 35.7 MVars	12.14	64.70	10.38	87.22	0.826	28.364	30.34
	DGs export 48 MW & absorb 23.7 MVars	15.60	85.00	12.00	112.60	0.847	26.719	33.60
Maximum	No DG	-	-	-	-	2.033	79.001	-
	DGs export 48 MW	-	-	-	-	2.302	76.816	-
	DGs export 48 MW & 35.7 MVars	12.70	67.10	9.80	89.63	2.482	80.186	7.79
	DGs export 48 MW & absorb 23.7 MVars	14.78	84.24	13.60	112.62	2.527	79.290	9.78

B. Simulation results of the case with multitple GSPs

Similar to the 1 GSP case, load flow simulations were carried out for the case with 3 GSPs (Fig. 2), with no DGs and when the DGs are exporting and absorbing reactive power and at minimum and maximum network load. Q-sensitivities seen at different GSPs were calculated using equation (1), with respect to the reference cases at minimum and maximum network loads.

TABLE II. shows the Q-sensitivities seen at different GSPs, the sum of Q-sensitivity at the 3 GSPs, P losses, Q losses and also the percentage of change in P losses compared to the reference case. TABLE II. shows that the total (summation) of the Q-sensitivities at all the GSPs have very similar values to the case with 1 GSP (TABLE I.). However, the results show that the reactive power injected by the DG are now divided between GSPs because of the interconnections at 132kV. The GSP which has a minimum electrical distance to the DGs (GSP2) has the highest Q-sensitivity. The increases of P losses are considerably reduced compared to the case with a single GSP (TABLE I.). No voltage excursions were recorded. Similar to the 1 GSP case, at minimum load P losses with DGs at all the operating modes are considerably higher than the case with no DGs.

IV. DISCUSSION AND CONCLUSION

This study, based on a part of South Wales network, shows that if generators are connected to the distribution network and absorb reactive power there will be a multiplier of around 1.1 in the reactive power drawn from the transmission system compared to that absorbed by the DG. Similarly, if the distributed generation exports reactive power the multiplier is around 0.9. If the power factor of the network load changes, then the multipliers change slightly.

The additional reactive power absorbed at the transmission level compared to the amount absorbed by the DGs is due to the inductive impedance of the downstream distribution network absorbing more reactive power while moving reactive power along the network to the DG. If there are multiple GSPs interconnected at higher 132 kV, this diverts some of the reactive power away from a particular GSP but the total reactive power flow at the distribution/transmission interface is the same as the 1 GSP case. There are increased P losses in the network, but unmanageable voltage variations were not found in the South Wales network.

This study shows that there is a potential for providing reactive power support from distribution networks to the transmission system. The technique presented in this paper is useful when different organisations are dealing with transmission and distribution systems. However, the increase in the active power losses in a distribution network during high reactive power loading creates a conflict of interest between transmission and distribution network operators. This requires a compromise between the reactive power loading required by transmission network operators and the operation with minimum active losses required by distribution network operators.

Welsh Power currently has 26 similar sites with gas fired generator sets across the UK and the methodology presented in this paper is directly applicable to those sites. The generators need to be operating to absorb the reactive power and at times of light load the value of electrical energy is low, but gas costs may be higher. Therefore, absorbing reactive power to support transmission level voltages may not be cost effective for the operators of gas fired generators under current commercial arrangements.The number of large, 5-50 MW, PV and battery systems that are connected at 33 kV is increasing rapidly [9], [10]. The technique presented in this paper is also useful for distribution connected solar PV farms and battery energy storage systems (BESS) using the reactive power capabilities of the voltage source converters.

However, the challenge is to devise a control scheme able to control the distributed generators at MV level to provide certain amount of controlled reactive power at transmission/distribution interface, without requiring a central controller to collect and process measurements of the whole system.

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APPENDIX

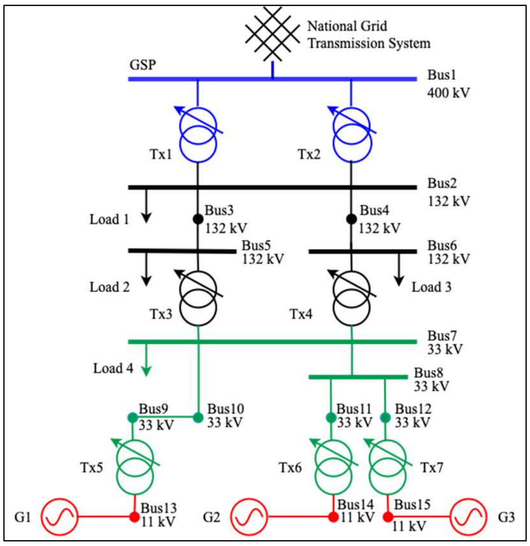

Fig. A.1. IPSA network diagram used for simulation studies with one GSP.

TABLE A.I. TRANSFORMER DATA

Trans-former	Positive sequence resistance, % on 100 MVA base	Positive sequence reactance, % on 100 MVA base	Min. tap (%)	Max. tap (%)
Tx1	0.0996	8.0568	-15	+5
Tx2	0.0996	8.0568	-15	+5
Tx3	1.0500	24.1990	-16	+15
Tx4	1.0500	24.0880	-16	+15
Tx5	0.0000	60.7210	-15	+15
Tx6	0.0000	60.7210	-15	+15
Tx7	0.0000	60.7210	-15	+15

TABLE A.II. GENERATOR DATA

Generator	Rated power (MVA)	Synchronous, d-axis reactance of the generator set, % on 100MVA base	Positive sequence resistance of the generator set, % on 100 MVA base
G1	8× 2.481	826	3.02
G2	8× 2.481	826	3.02
G3	8× 2.481	826	3.02

TABLE A.III. DISTRIBUTION LINE DATA

From Bus	To Bus	Positive sequence resistance, % on 100 MVA base	Positive sequence reactance, % on 100 MVA base	Susceptance
Bus 10	Bus 9	2.4895	2.3533	0.1877
Bus 7	Bus 10	8.1487	17.1577	0.1375
Bus 7	Bus 8	2.3806	4.0618	0.4917
Bus 8	Bus 11	0.0000	0.0100	0.0000
Bus 8	Bus 12	0.0000	0.0100	0.0000
Bus 4	Bus 6	0.3977	1.7396	0.6414
Bus 3	Bus 5	0.3977	1.7396	0.6414
Bus 2	Bus 4	0.0000	0.0110	0.1892
Bus 2	Bus 3	0.0000	0.0110	0.2141

TABLE A.IV. LOAD DATA

Load	Maximum P-demand (MW)	Maximum Q-demand (MVar)
Load 1	127.428	3.701
Load 2	41.882	1.665
Load 3	41.882	1.665
Load 4	14.900	0.000