MULTI-OBJECTIVE OPTIMAL POWER FLOW TO EVALUATE THE TENSIONS INVOLVED IN CONNECTING DISTRIBUTED GENERATION

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ABSTRACT

As part of the continuing drive for cleaner energy sources and more efficient delivery of electricity, regulators are looking to provide incentives for distributed generation (DG) developers and Distribution Network Operators (DNOs) to connect DG. A key question is whether these incentives will be goal congruent in encouraging both developers and DNOs to act in the common good. Using current UK incentives as a basis and, with the aid of multi-period multi-objective optimal power flow, the tensions and potential trade-offs involved in connecting DG are explored.

INTRODUCTION

As part of the 2005 UK distribution price control (DPC), DG is now charged Distribution Use of System (DUoS) charges rather than the full upfront cost of connection. The charges paid to the DNO consist of [1]:

- an annuity charge based on 80% of the cost of the reinforcement works required to connect the DG, over a 15 year life, at an agreed rate of return.
- an annual capacity charge of £1.50/kW of DG capacity installed (in lieu of direct recovery of the remaining 20% of the reinforcement assets).
- an annual operations and maintenance (O&M) charge of £1/kW of DG capacity installed.

These charges offer DNOs an incentive to connect DG by providing a return that is in excess of the normal regulated rate. It would also appear to be in line with the aim of developers which are, broadly speaking, to maximize returns by connecting as much DG as possible. There may be significant benefit to both parties in making best use of the existing network in order to minimise reinforcement costs. This would require both developers and DNOs to favour the most suitable sites while limiting connections at sites which may sterilize the network.

Unfortunately, the picture is complicated by other incentives given to UK DNOs in the 2005 DPC. A loss incentive scheme was introduced to encourage DNOs to manage losses effectively by rewarding loss reduction and penalizing increases relative to target levels. The annual target levels are set for each DNO by Ofgem and each unit of loss is valued at £48/MWh (in 2004 values). Given the broad U-shaped relationship between losses and DG penetration there is a risk that DNOs will be exposed when DG connects in significant volumes. Despite some protection for DNOs through limits on loss adjustment factors, the rewards available with the loss reducing effect of modest capacities of DG may be an incentive for DNOs to limit connections within their networks. This is particularly important given the relative magnitude of the incentives for connections and losses: £2.50/kW per year versus £48 per MWh.

A further major area where DG can have a significant impact is by deferring network reinforcement that would otherwise be required to meet load growth. The value of substituting DG for network capacity can be significant. While the value attributed to the deferral of network upgrades is heavily dependent on the reliability of peak power production, rewarding DG that defers network reinforcement would provide a valuable locational signal. Despite this there is currently no formal UK mechanism for benefit recognition.

Overall, there appears to be a degree of contradiction between the incentives for DG developers and DNOs. There is a need to examine the impact of these, and those offered by network deferral, on the desirability of connecting DG.

DNO AND DEVELOPER DG PREFERENCES

To explore the effect of these differing incentives on developers' and DNOs' preferences for DG connections, a multi-period multi-objective optimal power flow (OPF) has been developed. It determines optimal DG capacity within the technical limits on the networks based on the objectives of the parties. It extends the OPF methods of [2] and [3] and applies the ε-constrained multi-objective OPF technique of [4]. The multi-period approach represents the load duration curve as a series of discrete load states. This allows a more realistic estimate of the effect of loading and DG injections on losses. It also allows modelling of variable DG but here, for simplicity, DG is assumed to offer firm power. A simple case of network deferment benefit is modelled where specific network elements require reinforcement as demand increases, e.g., grid supply transformers approaching capacity. The benefit is independent of the DG location and the benefit applies to the entire DG firm capacity.

The multi-objective OPF problem simultaneously maximises the benefit of DG to the developer and DNO amongst a set of feasible solutions subject to a range of constraints. The analysis constrains DG capacity within existing network limits so there is no cost associated with network reinforcement to accommodate DG connection.

The developer's annual objective function is computed from a weighted sum across all the load bands (B, of $h(B)$ duration):

$$f_{DG} = \sum_{B} h(B) \sum_{g} \left(C_g^{DG}(B) - C_g^{CC} + D_{DG} \right) P_g \quad (1)$$

Here P_g is the capacity of the DG at bus g (MW), C_g^{DG} represents the developer's net revenue per kW of DG capacity connected (£/kW), C_g^{CC} is the combined capacity and O&M charge per kW of DG (£/kW) payable to the DNO, and D_{DG} is the portion of the benefit arising from deferral of network upgrades that accrues to the developer (£/kW).

The DNO objectives are significantly different and computed from a weighted sum across all the load bands:

$$f_{DNO} = \sum_{B} h(B) \left(\begin{array}{c} \sum_{g} \left(C_g^{CC} + D_{DNO} \right) P_g \\ + C_L (L_T(B) - L_A(B)) \end{array} \right) \quad (2)$$

Here, C_g^{CC} is the annual connection payment from the developer per kW of DG and D_{DNO} is network deferral benefit retained by the DNO. By valuing losses at C_L (£/MWh), the loss incentive rewards or penalises actual losses, $L_A(B)$, relative to the target level, $L_T(B)$.

The constraints on the growth of DG include: the energy source limiting DG unit size, a power factor constraint to ensure operation in power factor control mode, quality of supply standards requiring voltages to be maintained close to nominal as well as the thermal capacity of each circuit. Although feasible to include using the method presented in [3], fault level constraints have not been included here.

As the DNO and developer incentives are different it is likely that each will perceive different 'optimal' locations and capacities for DG. By comparing the two outcomes, and through the use of trade-off techniques, it may be possible to define a range of compromise solutions offering potentially better arrangements for DG under the current incentive scheme.

With multi-objective problems an infinite number of non-inferior solutions can be generated where improvement in one objective would result in degradation in the other. The decision-maker must subjectively choose the final compromise and different methods have been proposed to assist with this [5]-[7]. Here, an interactive approach based on the ε-constrained technique [4], [8] provides a set of non inferior solutions from which the most satisfactory solution can be subjectively chosen. The technique selects one objective function as the 'master' objective and the other 'slave' objectives become new constraints, which are partially defined by the trade-off preference of the decision-maker. The procedure then applies the concept of significant dominance to rule-out some alternatives leaving a 'knee set' containing non-significantly dominated ones [9]. The decision-maker would choose between these for their final choice either subjectively or using a direct method like max-min [10].

CASE STUDY

Implemented in Matlab®, the technique was applied to a 69-bus 11 kV radial distribution system with two substations. With complete network data given in [11], the network diagram is shown in Fig. 1 along with the location of seven potential DGs. The voltage limits are ±6% of nominal and the thermal limits for lines are 1.5 MVA. All DG are assumed to have fixed power factors of 0.9 lagging.

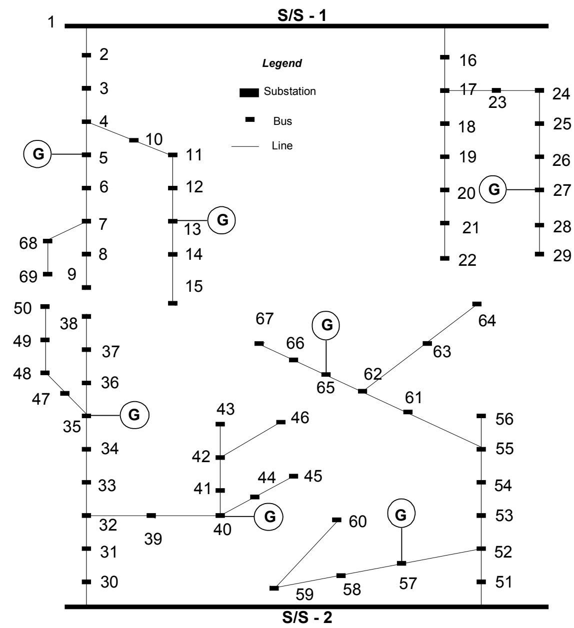

Fig. 1. 69-bus Network with DG unit locations

A load duration curve was assumed and discretised into four representative bands. The mean aggregate network load is just under 2.7 MW and weighted-average losses are 85 kW. The maximum load levels for each bus are given in [11]. The DNO incentives for the UK are applied with the DNO receiving £2.50/year per kW of DG with losses valued at £48/MWh. For illustration, the target loss level has been taken to be the initial loss level with no DG connected. The developer receives the proceeds of energy and carbon credit sales net of the fuel costs, DUoS payments, O&M, etc. The fixed cost of each DG is taken to be £1/hour and the linear net benefit function offers 1p/kW per hour at buses 13, 27, 35, 40 and 65 and 0.8p/kW per hour at buses 5 and 57.

Location	DNO	Developer	Trade-off solution
5	0.413	1.353	0.784
13	0.165	0.307	0.277
27	0.459	1.049	0.751
35	0.477	1.307	0.762
40	0.465	0.623	0.945
57	0.531	1.188	1.270
65	0.399	0.696	0.492
Total	**2.909**	**6.524**	**5.281**

Table 1 Optimal DG Capacities (MW)

Three separate analyses have been conducted to assess the implications of differing incentives for DNO and developer preferences for DG capacity. The first applies the benefits and costs as specified above. The second recognises an additional network deferral benefit for the DNO of £250/kW while the third envisages the DNO sharing this benefit with the developer, in the ratio 60:40. In each case, the opportunities for compromise between the parties are explored using trade-off analysis.

Results: Deferral Benefits Not Recognised

For the case without network deferral the DG capacities selected for each of the seven locations are given in the middle columns of Table 1. The total capacity that would be added by the DNO is less than half the 6.5 MW deemed optimal by the developer. The larger spread of capacities and the larger individual DG favoured by the developer is limited only by network voltage. Without the loss incentive the DNO's optimal connection would broadly match the developer (identical only if the developer had no locational preferences wherein value of the benefit is arbitrary [2]).
The inclusion of the loss incentive alters the benefit of DG perceived by the DNO and results in a more even spread of capacity. This is logical given the U-shaped loss trajectory: the loss incentive is tending to promote a more modest penetration of capacity to avoid the large losses associated with the reverse power flows from the larger DG capacity favoured by the developer.

The influence of plant capacity and siting on losses can be seen in Table 2. Relative to the target losses of 85 kW, the DNO's optimal arrangement sees losses reduce by 83% to an average of 15 kW. The developer's optimal scheme results in losses that exceed target by a third. The impact on losses across the load bands is more complex but the main observation is that DG operating during peak load offers benefits in terms of reduced losses.

	DNO	Developer	Trade-off solution
Developer Revenue [£/year]	176,920	465,640	365,290
DNO Revenue [£/year]	37,035	-13,405	18,120
Mean Losses (kW)	15	113	39

Table 2 DNO and Developer revenue and losses

The value attributed to losses has a significant impact on the parties' revenue under their respective, optimal, schemes (Table 2). With the DNO scheme the loss reduction provides cash inflows in excess of £37k/year. The developer's optimal set up would reduce DNO benefit by more than £50k/year. Imposition of the DNO optimal capacity sees developer revenue fall by 62% or just under £290k. These two contrasting situations see either the developer or DNO benefiting at the expense of the other. This highlights the potential for trade-off in finding a more equitable solution.

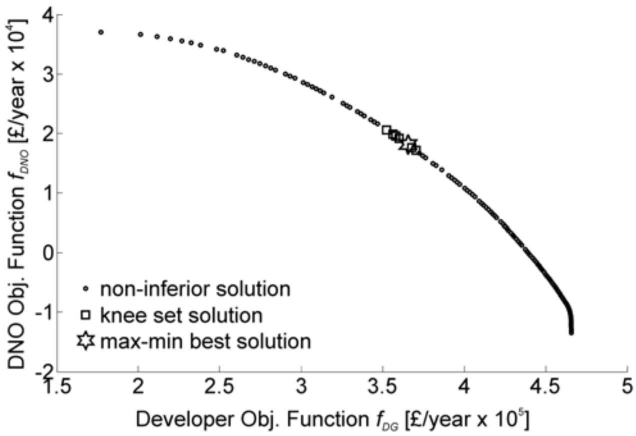

Fig. 2. Pareto solutions

Fig. 2 shows the large number of non-inferior solutions found by varying the trade-off preference of the decision maker for both developer and DNO objectives. The knee set was extracted by defining 'much worse' and 'significantly better' as 6.5% of the full range of values for the DNO and developer objectives. Concentrated towards the centre of the Pareto front, these solutions imply relative reductions in both parties' revenue of 20-25% for the developer and 45-54% for the DNO.
The changes in DG capacity implied by the knee set are illustrated using one of the solutions. As shown in Tables 1 and 2, for most locations the DG capacities and losses lie between the parties' optimal values. There is a consequent impact on both parties' revenues: the developer's falls by £100k relative to its own optimal but up £190k on the DNO arrangements. For the DNO the magnitude of the revenue changes are smaller but more significant as it avoids a loss.

It appears that for this case the non-inferior solutions of the knee set offer compromises that tend to raise the installed capacity without penalizing either party excessively.

Results: Deferral Benefits Recognised

When the network deferral benefits are recognised they raise the connection incentive by several orders of magnitude. By relegating the loss incentive this alters the behaviour of the DNO which opts to connect as much DG as the network technical constraints allow, i.e., it effectively matches the developer's optimal arrangements. At £250/kW, it raises DNO benefit to more than £1.6 million. With the developers' optimal capacity already limited by the network limits, and with no variation on benefit between locations in the network, sharing the deferral benefit has limited impact in this case. With the inclusion of network deferment benefit, the parties are now apparently incentivised to act in effectively the same way. As such, a trade-off is of minimal value.

DISCUSSION AND CONCLUSIONS

It is clear from this work that the incentives provided to DG developers and DNOs have a major impact on the parties' opinion of optimal DG penetration. Under the current UK incentive schemes, which do not formally recognise the potential benefits for network deferral, there are significant differences in terms of the amount of DG that the developer and DNO would optimally connect. It appears that for the DNO, the more significant incentive associated with loss reduction outweighs the direct benefit of connecting DG. The trade-off analysis applied in this case indicated that a series of compromises are available that could promote lower losses and higher DG capacities. However, as long as developers are not exposed directly to their impact on losses they will seek to connect as much capacity as possible and in the least number of units.

Although this work is based primarily on the current UK incentives, many of the outcomes should be applicable elsewhere as the objectives of DG developers and incentives for DNOs are broadly similar.

Overall, the work highlights the need for a proper distribution pricing scheme for the UK. Such a pricing scheme would provide economically efficient network prices and incentives arising from the marginal impact of each user on network costs. Such a scheme is to be implemented in the near future.

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