# Benefits of Distribution-Level Power Electronics for Supporting Distributed Generation Growth

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*Abstract*—It is expected that distribution networks will be required to accommodate large amounts of distributed generation. Keeping power flows and voltages within their limits will require either traditional infrastructure upgrades or active compensation. The form of active compensation (e.g. series, shunt, back-to-back, multi-terminal), quantity, and rating of compensator should be chosen to realize the best cost-benefit ratio. Distributed generator and compensator placement algorithms are used with a constrained power flow method to analyze a large number of case studies (using real UK network data). From these cases, assessments of compensator performance are made and summarized statistically. When considering incremental deployment across all networks, with the site of greatest benefit chosen at each increment, it is found that static synchronous compensators provide the most favourable cost-benefit ratio. In contrast, multi-terminal voltage-sourced converters tend to provide the greatest flexibility when considering uniform deployment across all networks. It is also observed that traditional reinforcement enhances the benefits provided by active compensation.

## I. INTRODUCTION

**D**ISTRIBUTION networks face a dual challenge as progress is made toward de-carbonizing energy supply: the introduction of distributed generation (DG) as well as an increase in peak customer demand with the adoption of electric vehicles. Both changes lead to an increase in peak currents in feeders and transformers as well as undesirable voltage excursions [1]. Mitigating this with traditional methods becomes more difficult as DG and load are increased, especially when large changes in loading and spikes in DG output occur in quick succession on the same feeder.

This paper will focus specifically on DG growth rather than increases in customer demand, though the operational issues surrounding both do intersect. Devices installed within a distribution network which are capable of sourcing real power back to the distribution (and ultimately, transmission) network can be considered as DG. This includes renewable sources such as wind turbines or photovoltaics, and also energy storage devices. Adoption of plug-in electrical vehicles will undoubtedly affect peak demand, but each vehicle could also be considered as a DG source if a vehicle-to-grid scheme is adopted [2]. DG integration has been much discussed (for instance in [3]) and in some regions, high penetrations of DG (photovoltaics) are already present [4], [5].

To avoid the aforementioned issues with DG growth, distribution network operators (DNOs) often prefer to connect DGs at higher voltages (33kV or 132kV in the UK) to reduce impact on voltages. In contrast, developers favour connection at lower voltages where associated connection and equipment costs are lower [6]. In the UK this would be the 11 kV distribution level [7]. Here, the effects of DG installation on network voltages are significant [8]. Traditional reinforcement with higher capacity lines and substation transformers or shorter feeders from substations placed at higher density could resolve these problems but at great expense. Active control of power flows and bus voltages through medium voltage (11 kV) distribution level power electronics (PE) is an alternative to infrastructure upgrades and will be the focus of this paper.

A wealth of information exists on the use of PE for the support of the transmission (high-voltage) grid. These devices are sometimes referred to as flexible AC transmission systems (FACTS) or custom power [9]. From these transmission network examples, many analogies can be made with application to distribution networks [10]. At the distribution level, it becomes more cost-feasible to utilize voltage-sourced converters (VSCs) to realize compensators due to less expensive components and larger production quantities of medium-voltage power electronic units, e.g. motor drives, VSC interfaced wind generation. While most literature surrounding the application of back-to-back or multi-terminal VSCs involves their use in high voltage (>200 kV) DC networks [11], a medium-voltage back-to-back installation utilized for power exchange between transmission grids (via step-up transformer) was described in [12]. This installation serves as a good example of the application of a medium-voltage back-to-back conversion system supporting a transmission network; however, its use is primarily for power exchange between transmission systems rather than controlling voltages or optimizing power flows in distribution networks. Of greater relevance is the use of voltage compensation in rural networks using active compensation to increase loading, which is discussed in in [13]. A similar look at control and coordination of active compensators for optimal power flow with increasing DG is also discussed in [14].

This paper expands on existing literature by providing a direct comparison of several device types, quantities, and ratings. To provide this comparison, the capabilities of various types of power electronic compensators to relieve network constraints and accommodate DG are assessed across several networks. The level of additional DG they allow a network to accommodate ($\Delta g$) and the reduction in required infrastructure upgrades required for a given penetration of DG ($\Delta u$) are the main performance metrics. Results are summarized for 593
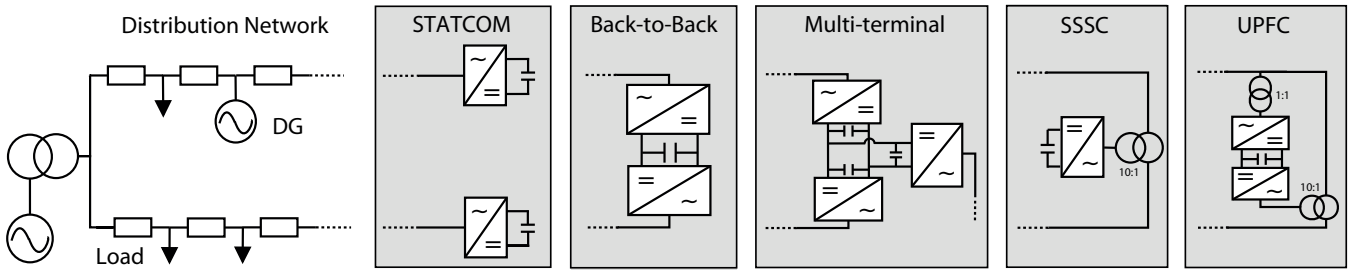
Figure 1: Distribution-level power electronics devices under study for network compensation

distribution networks, containing 11.6 GW of load and 5.3 million customer connections and including rural, urban and mixed networks with both underground and overhead lines. The goal of this paper is to identify which compensation type, rating and quantity is best under different conditions. Also compared is the deployment strategy, i.e., considering optimal incremental placement across all networks versus applying the same scheme uniformly to all networks.

## II. COMPENSATOR MODELING AND TYPES

The following compensator types are considered: static synchronous compensator (STATCOM), back-to-back (B2B) VSCs and multi-terminal (MT) VSCs, static series synchronous compensators (SSSC) and unified power flow controllers (UPFC). Fig. 1 gives an overview of these topologies. Each is made from an arrangement of VSCs. It is assumed that VSCs are capable of providing a controlled current while meeting grid interconnection standards. Literature on VSC topologies suitable for 11 kV applications is available in [15].

Compensators are modeled by considering them as controlled current sources connected to network nodes with constraints specified on the current and voltage at that node to reflect the unique behaviour of each compensator. These constraints, together with a summary of features and benefits, is given in Table I (post-fault restoration refers to the ability of the compensator to supply isolated areas of a network). Compensators will also be discussed in terms of their ability to exchange real (P) and reactive (Q) power, which defines a P-Q capability curve. It is emphasized that these curves differ from those established in literature for FACTS devices used in transmission networks with stiff grid connections. In the case of distribution networks with compensators installed at feeder endpoints, the entire network model needs to be accounted for in order to determine the capability curve (especially for series-type compensators). The example curves shown in Table I are intended to compare capability on an arbitrary network and consider device constraints only.

A STATCOM has the form of a VSC connected in shunt to a feeder. Since each STATCOM is only associated with a single network node, there is no necessity for an additional cable link installed between nodes. This will lower costs and planning constraints associated with device installation as compared with the other options, but feeder load balancing and post-fault resupply are not possible. The STATCOM is constrained such that it cannot exchange real power with the network.

Back-to-back and multi-terminal compensators are realized with two or more VSCs connected via a common DC link.

These devices allow for real power exchange between the AC front-ends as well as reactive power support. The device modeling constraints for back-to-back and multi-terminal compensators limit the current according to the device rating, ensure a real power balance between all VSCs, and put an upper limit on the output voltage. The reactive power output is limited by this voltage constraint.

SSSCs utilize a transformer connected in series between two network nodes to apply a series voltage, thereby controlling the impedance between those two points and influencing network power flows. The UPFC adds to this an additional shunt converter connected via a DC-link. The SSSC is constrained such that it cannot exchange any real power. In contrast, the series element of the UPFC can exchange both real and reactive power due to the presence of the shunt converter (the shunt converter current rating is set to match the rating of the series converter). The capability curve of the SSSC (and to a lesser degree, the UPFC) is determined not only by the device ratings themselves, but also by the network topology, constraints, and operating point as well as the device placement (note the asymmetric capability curve). The series voltages and currents of both devices are constrained according to the series transformer tap ratio (10:1). The potential to induce power flows greater than the VSC rating, e.g. 10 MVA between two nodes using 1 MVA VSCs, is a primary advantage but still network-dependent.

## III. ASSUMPTIONS AND METHODOLOGY

### A. Limitations to the Introduction of Distributed Generation

Limitations on the introduction to DG into a given distribution network come in the form of voltage, thermal, and fault-current limits. Only the first two of these are considered in this work. Taking the UK example, 11 kV networks have been designed to regulate the voltage to within $\pm 3\%$ of nominal [16]. This figure will be used in this study for determining voltage limits. The EN50160 standards presently define slightly looser limits [17], however there is discussion that they may be tightened in future [18]. The lowest of all seasonal thermal limits for all distribution feeders was used.

It was assumed that DGs operate as constant power sources with unity power factor in an un-constricted, uncoordinated, and unpredictable manner. When considering the impact of DG, the worst case in terms of both voltage control and feeder over-currents occurs when all DGs are exporting their maximum (peak) power and the network loading is at its minimum [16]. Evaluating at this operating point is intended to give a lower bound on allowable DG in a given network.
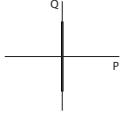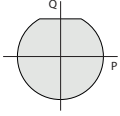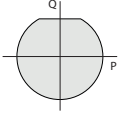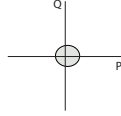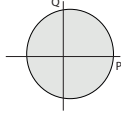
| | STATCOM | B2B | MT | SSSC | UPFC |
|---|---|---|---|---|---|
| **Feeder Connection** | None | DC-Link (async.) | DC-Link (async.) | Direct (sync.) | Direct (sync.) |
| **Real Power Exchange** | N | Y | Y | Limited | Y |
| **Post-Fault Restoration** | N | Y | Y | Y | Y |
| **Reactive Power Support** | Y | Y | Y | Limited | Y |
| **Partially rated converters** | Y | N | N | Y | Y |
| **Additional feeders Required** | N | Y | Y | Y | Y |
| **VSCs in Conduction** | 0 | 2 | 2 | 1 | 1 |
| **VSCs Per Device** | 1 | 2 | 2 | 1 | 2 |
| **PQ Capability Curve** | | | | | |
| **Solution Constraints**<br>$Vb$, $I_M$ - base l-n voltage and current<br>$S_{pu}$, per-unit rating on 10 MVA base<br>$p,k$ pair and device indices<br>$N_V$, no. of devices<br>$Is$, current between nodes<br>$Ish$, shunt current | $P_{k,1}=0$<br>$I_{sh} \le S_{pu}I_M$<br>$V_t \le 1.2V_b$ | $P_{k,1}+P_{k,2}=0$<br>$I_s \le S_{pu}I_M$<br>$V_t \le 1.2V_b$ | $\displaystyle\sum_{p=1}^{N_V}P_{1,p}=0$<br>$I_s \le S_{pu}I_M$<br>$V_t \le 1.2V_b$ | $P_{k,1}=0$<br>$I_s \le 10S_{pu}$<br>$V_t \le 0.1V_b$ | $P_{k,1}=P_{k,2}$<br>$I_{sh} \le S_{pu}I_M$<br>$I_s \le 10S_{pu}$<br>$V_t \le 0.1V_b$ |

Table I: Summary table for compensators under study

## B. Network Operation Assumptions

UK distribution networks perform their automatic voltage control (AVC) functions at the main (33kV/11kV) substation (MSS) via an on-load tap changer (OLTC), occasionally with additional voltage control applied by switched banks of capacitors or reactors. While it is important to keep in mind the differences in operation between the AVC schemes used in UK distribution networks and those in the rest of the world, most still rely on OLTCs and therefore do not provide the near-instantaneous response associated with power electronic compensation. In addition, the AVCs in distribution networks have traditionally been designed with the assumption of uni-directional power flows. For this reason, present operating schemes may be less compatible with the introduction of DG. It is also important to note that DGs can change their output between almost zero and full power rapidly, more so than fluctuations in aggregate customer demand. Traditional OLTC voltage control methods may be inadequate for this reason and are therefore not considered for use in conjunction with active compensation.

A set-point must be chosen for the OLTC. It will be assumed in this study that the tap set-point is set by the AVC scheme according to the loading condition while assuming zero DG output. For most networks, there are several viable tap positions at each loading condition which allow network voltage constraints to be met. Good practice suggests choosing a set-point that minimizes the number of tap-change operations required to span all loading conditions [19]. To find this point, the set-point range at minimum loading is compared with the set-point range at peak loading and the point closest to the intersection of these two sets is chosen.

It is assumed that the compensation scheme will be centrally controlled, and that the necessary communication links and measurements are in place to achieve this.

## C. Supporting Software and Routines

A suite of software tools was developed in order to process network data and perform the described studies more efficiently. The following sections briefly describe the most relevant software components and the routines used within.

*1) Network Modeling and Load Flow:* The method of representing networks and obtaining the load-flow solution follows from that presented in [20]. This is a direct-solution approach in which the node voltages and branch currents are expressed as an explicit function of compensator currents and OLTC voltage set point. The resulting solution is equivalent to that given by the Newton-Rhaphson method.

In determining a level of allowable DG, the network (voltage and thermal) limits and device constraints (Table I) define a solution space with compensator output currents serving as decision variables. A certain quantity of DG is considered feasible if the solution space is non-empty, i.e., the compensators installed can provide output which cause all network and device constraints to be met.

*2) Compensator Placement:* The first step in choosing compensator placement is the separation of the network into unconnected or weakly connected areas. This is achieved by branching out from the MSS in stages while selecting feeders which supply weakly connected areas, i.e., three branches from the MSS could separate the network into three areas. In most cases, the number of segments is increased as the algorithm branches out from the MSS. As each grid-coupled VSC will be assigned an area to compensate, it is necessary to branch out until the number of segments is greater than $n$ (or $2 \cdot n_v$ in the case of the SSSC). If the number of areas is greater than $n_V$, a subset of areas is chosen according to the number of customers (measured in total load) that would benefit from the compensator. This gives the compensator the greatest benefit for post-fault resupply. Areas are then paired (for point-to-point compensators) or grouped (for multi-terminal compensators) according to geographical distance between the groups.

After areas have been chosen, nodes within a given area are ranked according to the voltage difference between themselves and the MSS. This will generally result in feeder endpoints being selected, which also allows for maximum benefit for restoration in post-fault scenarios. Node selection is also weighted by the ratings of the surrounding feeders to avoid installing compensators in segments of the network which cannot carry the rated compensator output current.

In summary, the placement routine considers geographical distance, degree of control over node voltages and branch currents, and the amount of load that could be restored via the compensator link should a portion of the network become isolated. Compensator sites are chosen by assigning a weight to the above properties of the area or node, depending on the stage of the algorithm. A balanced weighting scheme was used for the results presented in this paper, though it is possible to achieve different goals by changing the weights, e.g., to reduce geographical distance between installations.

*3) Infrastructure Upgrades:* In addition to considering allowable DG before any infrastructure upgrades are applied, it is also of interest to consider infrastructure upgrades (in $kA-km$) required to support DG growth and as a complement to active compensation. If a certain level of DG is infeasible, even with active compensation, feeder upgrades are applied until the compensator is able to bring the network voltages and currents within their constraints. Choosing which feeder or transformer to upgrade is achieved in two stages: To begin, it is determined whether any thermal limits are breached. If so, they are treated as an upgrade priority and the overloaded feeder with the lowest $kA - km$ will have its ampacity increased and impedance reduced. If the problem is still infeasible, this is repeated until no thermal limits are breached. With no overloads, feeders with the largest voltage drop are upgraded one-by-one until a solution is found. Upgrading feeders one-by-one is computationally inefficient, but ensures that unnecessary upgrades are avoided and therefore results in a better comparison between schemes.

*4) Distributed Generator Placement:* Maximum DG penetration will vary according to how DGs are distributed throughout a given network. For this reason, different DG placement schemes have been considered. The schemes are illustrated in Fig. 2 and described as follows:

- **Uniform Placement** - DG spread uniformly throughout all network nodes representing a large number of small residential DG installations
- **Clustered Placement** - large amounts of DG are installed in areas of low load density representing large installations initiated by DG developers
- **Mixed Placement** - a combination of the clustered and uniform placement schemes

To realize these schemes, DG quantities at each node are incremented throughout a given network, with the magnitude of increment weighted according to surrounding load density and the placement scheme. For the sake of brevity, results presented in this paper are considered for *Mixed Placement*. Results can be scaled according to Fig. 3 (of the following section) to give an idea of how the other two placement scenarios affect the results.

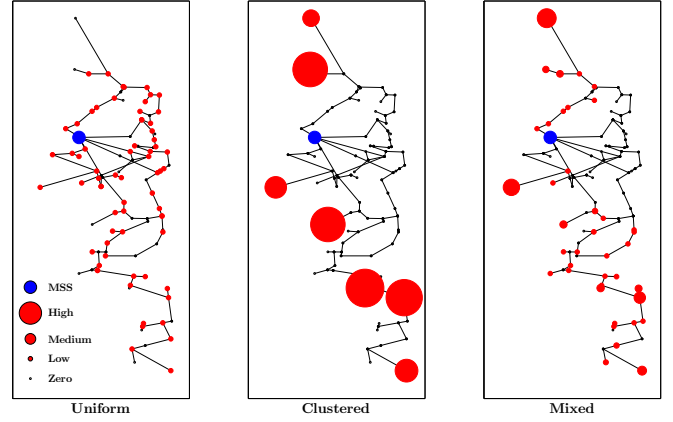Distributed Generator Placement Schemes



Figure 2: Topology of one network under study, and illustration of different DG placement schemes

## IV. ACCOMMODATING DISTRIBUTED GENERATION

Two different compensator deployment schemes are considered: uniform and incremental. Uniform deployment refers to a particular compensation scheme applied to all network datasets with the resulting performance summarized by statistical mean and variance. Conversely, incremental deployment refers to adding compensators one-by-one to the region encompassing all networks under study. With each increment, an installation site which yields the the greatest marginal benefit is chosen.

The following symbols will be used when presenting results:

| | |
|---|---|
| $g, \bar{g}, G$ | Individual and mean feasible DG penetration per network with uniform deployment and total DG across all networks for incremental deployment [*MW*] |
| $u, \bar{u}, U$ | Individual and mean feeder upgrades per network with uniform deployment and total upgrades across all networks with incremental deployment [*kA-km*] |
| $\sigma^2$ | Variance in uniform placement results |
| $\Delta x$ | Marginal increase in performance metric after compensation, where $x = g, u, G$ or $U$ |
| $n_v, N_V, S_V$ | Quantity of VSCs used with uniform deployment in each network, total with incremental deployment across all networks, and the corresponding MVA rating |
| $N, M$ | The sample population used in the presented study and the metric used for sub-categorizing this population |

Section IV-A will discuss how to interpret the mean and variance figures presented in the following sections. Section IV-B first considers $\Delta g$ for uniform deployment with an untouched infrastructure, i.e., how much DG can be supported without requiring any transformer or feeder upgrades. Networks can accommodate more DG if some infrastructure upgrades are permitted, which will be considered Section IV-C. Section IV-D alternatively considers the $kA - km$ required to support a certain quantity of DG by comparing a selection of cases. Finally, results for incremental deployment will be given in Section IV-E.

### A. Interpretation of Results

Distribution networks tend to follow similar design principles, but are all very unique. They will therefore accommodate different DG quantities with a large variance. By choosing a metric by which to classify different types of networks which

correlates well with $g$, the variance of results can be reduced and trends can be identified with respect to network type. It is intuitive that $g$ will be affected by the ampacity, impedance and length of circuits in a given network. Several combinations of these parameters were evaluated using the Spearman Correlation Coefficient ($\rho$), until the following metric, $M$, was found to have the best correlation ($\rho = 0.65$):

$$M = \frac{1}{\frac{1}{N_F} \sum_{i=1}^{N_F} \frac{(Z_i L_i)^{\frac{1}{4}}}{A_i^3}} \qquad (1)$$

where $N_F$ is the total number of feeders in the network, $Z_i$ is the magnitude of the feeder impedance in ohms, $L_i$ is the length of the feeder in $km$, and $A_i$ is the rating of the feeder in $kA$. Networks with a large $M$ tend to be urban (short feeders, high rating, low impedance) while a small $M$ suggests a rural network (long feeders, high impedance, low rating).
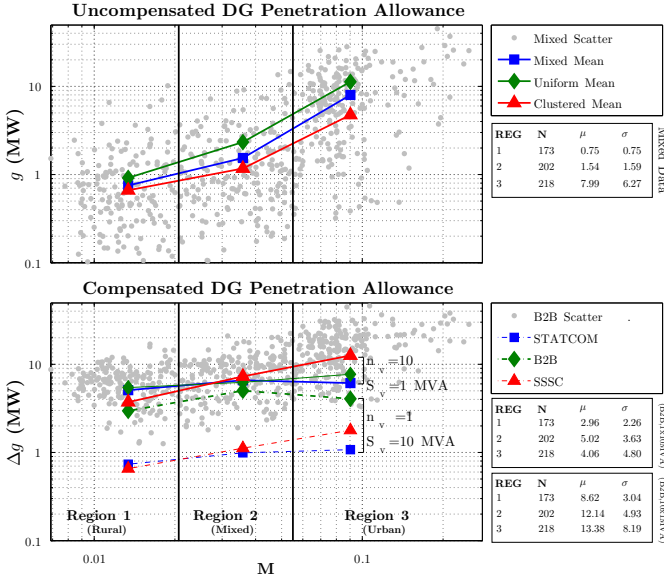


Figure 3: Allowable DG correlation with classification metric

The upper plot of Fig. 3 shows the uncompensated $g$ versus $M$ for the different DG placement scenarios. The scatter plot represents $g$ for the 593 individual networks exposed to *mixed* DG *placement*. The population is divided into three roughly equal subsets or regions, with each corresponding to a particular network type (rural, mixed and urban) and the mean value of that subset is taken. This division reduces the sensitivity to outliers and ensures that mean values are taken for similarly sized sub-populations when forming a trend-line.

With this classification scheme, urban networks tend to support larger absolute quantities of DG, but with a greater variance. In addition, clustered DG placement allows for the lowest levels of DG and uniform placement the highest. This is largely because clustered placement increases power flow through a single feeder path, whereas power flows in the uniform placement scheme are spread amongst several circuits.

Correlation of $M$ with the incremental benefit, $\Delta g$ (observed in the lower plot of Fig. 3) is found to be much lower. The implication here is that the level of benefit provided by a compensator is not affected significantly by the network type.

| $S_V$ | $n_v$ | Unc. | | STAT. | B2B | MT | SSSC | UPFC |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | $\frac{dg}{dM}$: 55.5 | $\frac{d(\Delta g)}{dM}$: | 0.4 | - | - | 7.9 | - |
| | 2 | - | | -3.9 | -3.9 | - | 14.2 | 3.2 |
| | 3 | - | | -5.6 | - | -5.7 | 24.5 | - |
| | 6 | - | | -10.6 | -8.7 | -8.9 | 40.9 | 2.1 |
| | 10 | - | | -12.2 | -7.0 | -9.4 | 57.5 | 10.7 |
| 10 | 1 | $\frac{dg}{dM}$: 55.5 | $\frac{d(\Delta g)}{dM}$: | 0.8 | - | - | 7.9 | - |
| | 2 | - | | -5.5 | -4.2 | | 14.2 | -4.0 |
| | 3 | - | | -8.2 | - | -3.5 | 24.5 | - |
| | 6 | - | | -15.5 | -8.6 | -4.6 | 40.9 | -5.7 |
| | 10 | - | | -17.0 | 4.6 | 16.9 | 57.5 | 2.1 |

Table II: Sensitivity of results to network type

The exception to this is found with the SSSC, which is more sensitive to network type as described in Section II.

The slopes of the sub-set mean values is then used to describe the sensitivity of $\Delta g$ to variations in $M$. Table II shows the resulting sensitivity for various compensation scenarios. It is observed that the STATCOM varies negatively with $M$, suggesting that this device is slightly more suited to rural networks. $\Delta g$ of the SSSC varies positively with $M$ to a large degree, suggesting that SSSCs will benefit urban networks more. Other compensators do not appear to have a notable trend. The sensitivity to $M$ also tends to increase slightly with $S_V$ and $n_V$ in most cases, as does the overall magnitude of $\Delta g$.

While this paper presents a non-parametric statistical study, it is useful to know how the samples are distributed when interpreting the mean ($\mu$) and variance ($\sigma^2$) figures presented. Fig. 4 shows a histogram of $\Delta g$ for a $n_v = 6$. The histogram suggests a skewed probability distribution type, and the gamma distribution was chosen as it was able to most closely fit the largest number of scenarios. A trimmed $\mu$ was used as the measure of central tendency due to the presence of closed-form expressions relating $\mu$ and $\sigma^2$ to shape parameters for the gamma distribution, allowing the reader to reconstruct it. By presenting the mean the total benefit across all networks can also be calculated, e.g. $G = N \cdot \Delta g$. In most cases, both the variance and mean rise with an increased $S_V$ and $n_V$. Despite this increase in variance, the variance to mean ratio tends to lower with increased $S_V$ and $n_V$ (see Fig. 5).
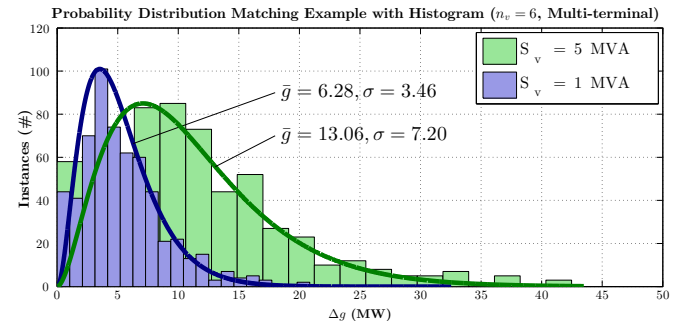


Figure 4: Histogram with scaled and fitted gamma probability distribution of $\triangle g$
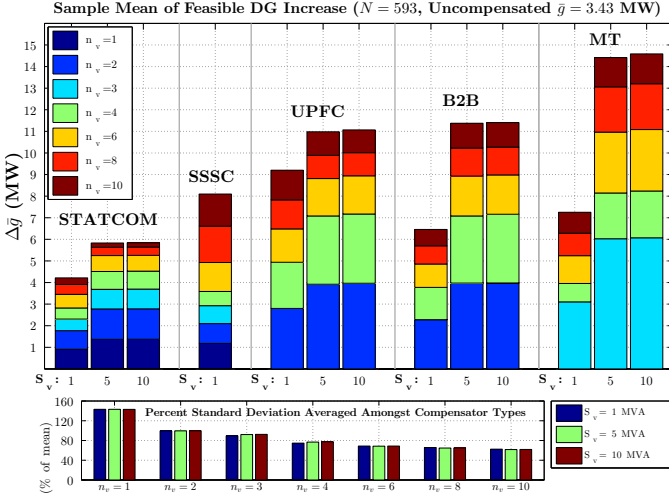
## B. Uniform Deployment of Compensators



Figure 5: Results of marginal increases in allowable DG penetration with compensation and summary of variance

The resulting mean $\Delta g$ values are shown in Fig. 5 for zero feeder or transformer upgrades. In general, the rule of diminishing returns holds true:

- Increasing $S_V$ from 1 MVA to 5 MVA has a much greater effect than increasing the ratings from 5 MVA to 10 MVA
- For most compensator types, the marginal benefit of increasing $n_V$ is lowered with rising $n_V$

Some additional observations are:

- UPFCs and SSSCs with low $S_V$ perform better than back-to-back converters of equivalent rating
- The multi-terminal option performs the best in most cases

UPFCs and SSSCs perform better than the B2B at low rating primarily due to the fact that the series element can exchange more power than its converter rating of 1 MVA, which is not the case for the B2B.

The SSSC has the advantage of requiring only a single VSC to interconnect two network areas, resulting in more widespread compensation given the same quantity of VSCs, i.e., for 10 VSCs, 20 areas could be compensated. By comparison, the 10 VSCs could be used to form 5 UPFC devices which only provide compensation to 10 network areas. For this reason, the SSSC performs relatively well despite having a much smaller capability curve than the other compensator types. It should also be considered that SSSC benefits are sensitive to network type and placement. SSSC performance can therefore be exploited by choosing an appropriate network for installation and siting to maximize power flow capability.

Table III shows competition results from direct comparison of a selection of different compensation schemes. This table gives a probability as to whether one compensator will outperform another based on individual competitions performed across the sample population. The STATCOM and SSSC are shown to be fairly evenly matched, while the UPFC frequently outperforms the SSSC despite the SSSC providing more widespread compensation for a given $n_V$. The UPFC at 1 MVA will tend to outperform a 1 MVA back-to-back compensator, but at 5 MVA their performance is similar.

| | | **P (A > B) / P (A < B)** | | | |
|---|---|---|---|---|---|
| **A vs B** | **$S_V$** | **$n_V = 1$** | **$n_V = 2$** | **$n_V = 4$** | **$n_V = 6$** |
| STATCOM vs SSSC | 1 | 0.31/0.39 | 0.47/0.40 | 0.48/0.47 | 0.44/0.53 |
| SSSC vs UPFC | 1 | - | 0.25/0.58 | 0.26/0.68 | 0.27/0.70 |
| UPFC vs B2B | 1 | - | 0.35/0.18 | 0.53/0.23 | 0.66/0.24 |
| UPFC vs B2B | 5 | - | 0.05/0.08 | 0.18/0.15 | 0.25/0.29 |
| MT vs B2B | 10 | - | - | 0.44/0.02 | 0.63/0.02 |

Table III: Competition table for select compensation schemes

## C. Infrastructure Upgrades and Compensation Combined

With upgrades to infrastructure ($u$), $\Delta g$ can be increased further. Fig. 6 shows the relationship between ($g, \triangle g$) and $u$ for 4 x 1 MVA VSCs of varying compensator types. Only feeder upgrade allowances are considered (not transformer upgrades) accounting for the differences with Fig. 5.

These results suggest that infrastructure upgrades and active compensation will complement each other up to a large number of infrastructure upgrades, i.e., $\Delta g \propto u$.. Compensation schemes with different $S_V$ and $n_v$ follow similar trends.
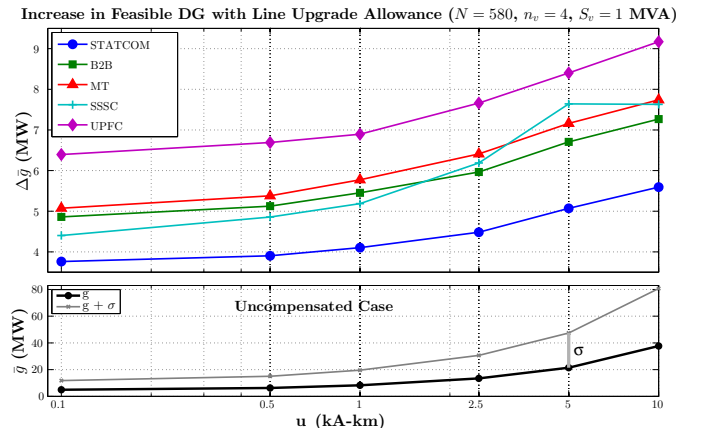


Figure 6: Allowed DG with increasing line upgrade allowances

## D. Feeder Upgrades with DG Growth

Feeder upgrades required to support a certain level of DG are considered for uniform deployment of compensation schemes. A selection of results for two different values of $G$ are shown in Fig. 7. In addition to comparing compensator type, the selected results compare a small number of 10 MVA compensators and a large number of 1 MVA compensators. In the case of the multi-terminal compensator the rating is reduced to account for the additional terminal (minimum $n_v = 3$). This intent is to compare cases which would have roughly similar costs, i.e., 10 x 1 MVA units would require additional installation sites but have a lower $n_V \cdot S_V$ product than the 2 x 10 MVA case.

For a small amount of DG present ($g = 5$ MW), 6.1 kA-km of line upgrades are needed if no compensation is used. The top plot shows the difference in required upgrades with active compensation. Compensator performance does not vary significantly between types, especially so for a large $n_V$. With more DG present ($g = 20$ MW), the trends in $\Delta u$ are similar
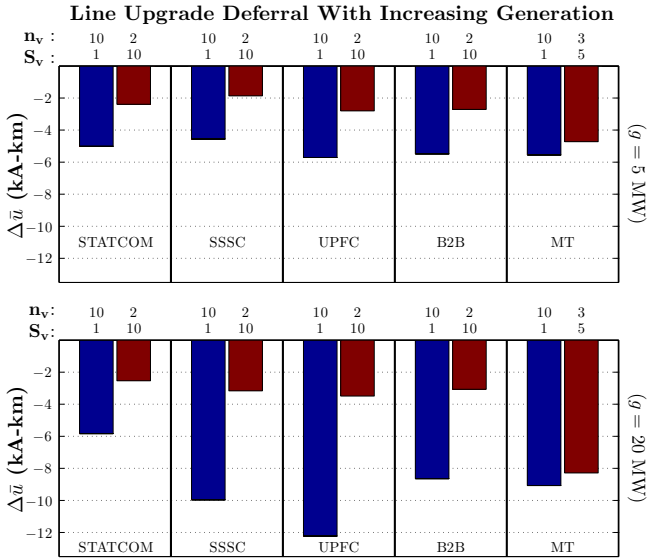
Figure 7: Feeder upgrades avoided with the use of compensation for different levels of installed DG. For the uncompensated cases at $g = 5\ MW, u \approx 6.1$ ($\sigma \approx 8.4$) kA-km and for $g = 20\ MW, u \approx 20.1$ ($\sigma \approx 22.7$) kA-km

to that of Fig. 5 with approximately 20 kA-km required for uncompensated networks. The 5xUPFC configuration (10x1 MVA VSCs) offers the greatest decrease in upgrades. These results suggest that it may make sense to install a STATCOM then later upgrade to a B2B, or move from SSSCs to UPFCs, as DG levels increase to delay costs associated with the more expensive options.

This study varies from that of Fig. 6 despite also showing a relationship between $g$ and $u$. Here, every network is forced to accommodate a fixed $g = g_0$, requiring the DNO to upgrade the network as needed so as not to limit DG growth. In the previous case, $u$ is fixed at $u_0$ and the maximum DG in a given network (at $u = u_0$) is considered. The results show that the latter is a more efficient use of upgrades to improve the total installed generation across all networks ($G$). This is primarily due to the fact that putting a cap on $u$ discourages DG installations in networks that are inherently poor at accommodating DG.

### E. Incremental Deployment of Compensators

Another way of comparing compensator types is to consider the incremental deployment of compensators across all networks; that is, at each increment, choose a network to install a new or additional compensator that will maximize total generation, $G$. The upper plot of Fig. 8a shows the resulting $\Delta G$ versus $N_V$ with incremental deployment, and also compares the case of uniform deployment in which four 5 MVA and 1 MVA compensators are installed in every network. It is shown that this optimal incremental deployment results in a much greater benefit for a given $N_V$ compared applying the same scheme to all networks, with a difference of 2.4 GW and 1.6 GW across all networks for the example cases shown on this figure.

Another measure of performance is the benefit-cost ratio, $\frac{\Delta G}{N_V \cdot S_V}$, versus $N_V$ (shown in the lower plot of Fig. 8a

with a log-scale to show additional detail). It is assumed that cost will scale with the quantity and rating of VSCs utilized. In contrast to the results observed for uniform deployment, the SSSC and STATCOM tend to perform better for wide deployment up to a certain $N_V$ (approximately 100 to 200 VSCs). To explain this, consider that in Fig. 5 that the greatest $\Delta g$ tends be with the first device installation. STATCOMs and SSSCs utilize a single VSC to provide compensation, and therefore this initial large $\Delta g$ can be applied a greater number of networks for a given $N_V$.

If considering 5 MVA VSCs, the STATCOM offers the best performance initially, but is overtaken by other options past $N_V = 100$. Other studies have indicated that the benefit from the STATCOM is reduced drastically if working in conjunction with existing OLTCs, as both the OLTC and STATCOMs have similar effects on the network.

This study shows that utilizing low capacity VSCs offers a better benefit-cost ratio regardless of the compensator type.
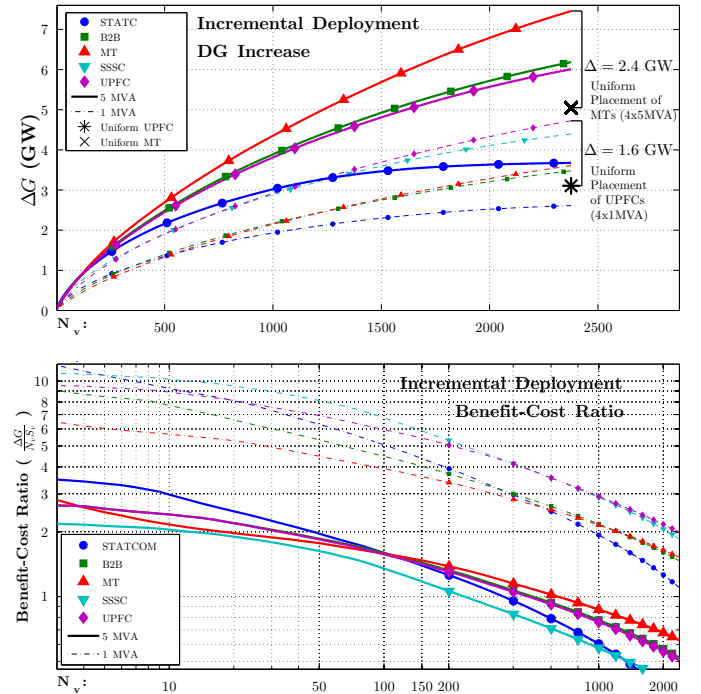


Figure 8: Total $\Delta G$ and benefit-cost ratio for incremental deployment of compensators

### V. CONCLUSIONS

The studies presented consider the use of active compensation with power electronics to increase the level of DG that can be accommodated in distribution networks. A constrained power flow method was used to model devices and determine the capacity for DG on a particular network. A method was devised for automatic placement of compensators and DG to enable a large number of cases to be analyzed. The sample case population consisted of data from nearly 600 UK distribution networks. Varying quantities of shunt, series, back-to-back and multi-terminal compensators of different ratings were considered.

The network data contained an assortment of topologies and hence a metric was developed to aid with classification. The

allowed DG capacities in uncompensated networks correlate well with this metric, while the marginal DG capacities afforded by compensation are not as strongly correlated (series-only devices excluded). As marginal benefits are less sensitive to network type, a solution can be chosen to benefit a wider range of networks. For compensation (type, quantity and size) applied uniformly across the population, results are expressed as the mean and variance of this margin. For incremental deployment across all networks, a total benefit is used.

Another measure of performance is the ability to defer of traditional reinforcement as DG levels increase. For small amounts of DG, performance is not as varied as with larger amounts. This suggests that it may make sense to install less costly STATCOMs and later interconnect them to form back-to-back compensators as DG levels rise. In addition, benefits of compensation are found to increase with further allowance of infrastructure upgrades, suggesting that reinforcement can complement active compensation in accommodating DG.

With compensation applied incrementally to one network at a time, the best cost-benefit ratio results from using low capacity converters (with 1 MVA SSSCs and UPFCs leading). At 5 MVA, the STATCOM offers the best performance up to a certain quantity of installations, then it is overtaken by other options. Although larger numbers of compensators with lower ratings offer better performance, higher ratings may be needed to allow post-fault resupply to adjacent feeders.

If considering the performance with compensation schemes uniformly deployed across all networks, the 10-MVA multi-terminal compensator offers the greatest flexibility. The back-to-back compensator offers only slightly better performance than the UPFC at higher ratings, but has the added advantage of being able to isolate connected feeders from disturbances. At 1 MVA, the UPFC and SSSC compensators offer the best performance. SSSCs were particularly effective in urban networks where they achieve power exchanges between network sections greater the rating of the converters themselves. A low capacity UPFC capable of fault-blocking would represent the greatest level of benefit to each network with a considerably lower cost and physical footprint than multi-terminal or back-to-back compensators.

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