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 (DG). 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, multiterminal), quantity, and rating of the compensator should be chosen to realize the best cost-benefit ratio. Distributed-generator and compensator placement algorithms are used with a power-flow and constraint satisfaction algorithm to analyze a large number of case studies (using real U.K. 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 favorable cost-benefit ratio. In contrast, multiterminal voltage-source 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.**

***Index Terms*—Back-to-back, D-FACTS, distributed generation (DG), flexible ac transmission systems (FACTS), multiterminal, soft open points (SOPs), SSSC, STATCOM, unified power-flow controller (UPFC).**

I. INTRODUCTION

DISTRIBUTION networks face a dual challenge as progress is made toward de-carbonizing the 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 intersect. Devices capable of sourcing real power to the distribution (and, ultimately, transmission) network can be considered as DG. This includes renewable sources, such as wind turbines or photovoltaics, and could also include distributed energy resources (DERs), such as energy storage devices. The adoption of plug-in electrical vehicles will undoubtedly affect peak demand, but each vehicle could also be considered as a DER 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].

In the U.K., DG developers or owners are generally separate parties from the owners of the infrastructure. To avoid the aforementioned issues with DG growth, distribution network operators (DNOs) often prefer to connect DGs at higher voltages (33 kV or 132 kV in the U.K.) to reduce impact on voltages. In contrast, developers favor connection at lower voltages where associated connection and equipment costs are lower [6]. In the U.K., 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 to the DNO. 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 the application to distribution networks [10]. At the distribution level, it becomes more cost feasible to utilize voltage-source converters (VSCs) to realize compensators due to less expensive components and larger production quantities of medium-voltage (MV) power-electronic units (e.g., motor drives and VSC-interfaced wind generation). While most literature surrounding the application of back-to-back or multiterminal VSCs involves their use in high-voltage (HV) ($>$200-kV) dc networks [11], an MV 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 an MV 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

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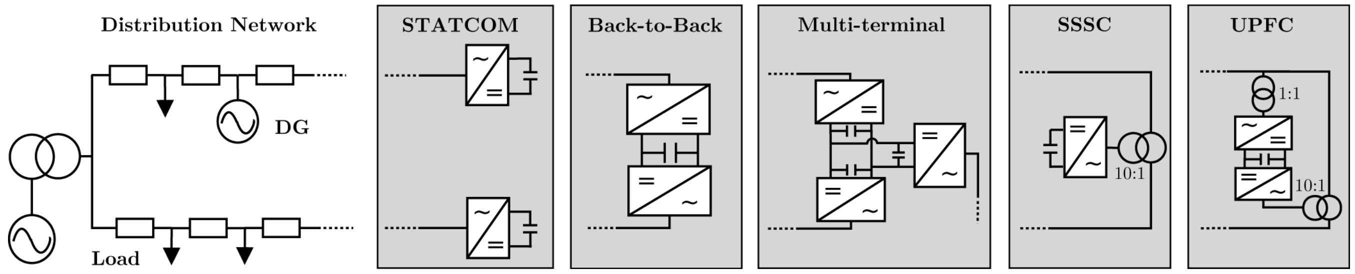
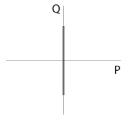
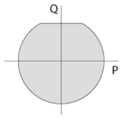
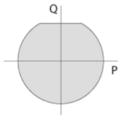
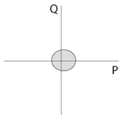
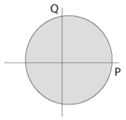


Fig. 1. Distribution-level power electronics devices under study for network compensation.

TABLE I
SUMMARY TABLE FOR COMPENSATORS UNDER STUDY

	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	Min 3	1	2
PQ Capability Curve					
Solution Constraints Vb, I_M - base l-n voltage and current S_{pu}, per-unit rating on 10 MVA base k,p device set index and VSC sub- index n_v, no. of VSCs Is, current between nodes Ish, shunt current	$P_{k,1} = 0$ $I_{sh} \leq S_{pu} I_M$ $V_t \leq 1.2V_b$	$P_{k,1} + P_{k,2} = 0$ $I_s \leq S_{pu} I_M$ $V_t \leq 1.2V_b$	$\sum_{p=1}^{n_v} P_{1,p} = 0$ $I_s \leq S_{pu} I_M$ $V_t \leq 1.2V_b$	$P_{k,1} = 0$ $I_s \leq 10S_{pu}$ $V_t \leq 0.1V_b$	$P_{k,1} = P_{k,2}$ $I_{sh} \leq S_{pu} I_M$ $I_s \leq 10S_{pu}$ $V_t \leq 0.1V_b$

[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 comparison of device types, quantities, and ratings. The capabilities of these power-electronic devices in relieving network constraints and accommodating DG are assessed across several networks. The level of additional DG they allow a network to accommodate (Δg) and the reduction in required infrastructure upgrades required for a given penetration of DG (Δu) are the main performance metrics. For the studies performed, data were provided by U.K. DNOs for 593 distribution networks across the U.K., 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 are the best under different conditions. The deployment strategy is also compared (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 multiterminal (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 behavior of each compensator. These constraints, together with a summary of features and benefits, is given in Table I (postfault 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 the 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 compared with the other options, but feeder load balancing and postfault resupply are not possible. The STATCOM is constrained in that it cannot exchange real power with the network.

Back-to-back and multiterminal 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 multiterminal 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 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 transferred using 1 MVA VSCs) is a primary advantage but again the ability to do so is network and placement dependent.

III. ASSUMPTIONS AND METHODOLOGY

A. Limitations to the Introduction of DG

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 paper. Taking the U.K. example, 11-kV networks have been designed to regulate the voltage to within ±3% of nominal [16] based on performance targets suggested by DNOs for similar networks. 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 the future [18]. The lowest of all seasonal thermal limits for all distribution feeders was used. It should be considered that a larger voltage tolerance will often result in greater feasible DG capacity on a given network, depending on whether voltage or thermal limits are the dominant limiting factor.

It was assumed that DGs operate as constant power sources with unity power factor in an unconstricted, uncoordinated, and unpredictable manner. When considering the impact of DG, the worst case in terms of both voltage control and feeder overcurrents occurs when all DGs are exporting their maximum (peak) power and 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.

B. Network Operation Assumptions

U.K. distribution networks perform their automatic voltage control (AVC) functions at the main (33 kV/11 kV) substation (MSS) via an onload tap changer (OLTC), occasionally with additional voltage control applied by switched banks of capacitors or reactors. While it is important to keep in mind operational differences between the AVC schemes used in U.K. distribution networks and those used elsewhere, most still rely on OLTCs and therefore do not provide the relatively fast response associated with power-electronic compensation. In addition, AVC schemes in distribution networks have traditionally been designed under the assumption of unidirectional 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 may be inadequate for this reason and are therefore not considered to operate in conjunction with active compensation.

A voltage set-point must be chosen for the OLTC. It will be assumed in this study that the AVC scheme adjusts the tap set-point according to the loading condition while assuming zero DG output. This assumption represents a worst case regardless of whether the OLTC tap is set according to demand schedule or measurement feedback, as the rise in generator output is not anticipated and the response from a feedback-based control would be comparatively slow. 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. Sections IV and V 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, with the shunt impedance at each node varied at each iteration until the apparent power absorbed at each bus meets its reference value within a certain tolerance. The resulting solution is equivalent to that given by the Newton–Raphson method. When used to formulate an optimal power-flow problem with a large number of nodes (often seen in distribution networks), convergence was achieved for nearly all scenarios tested. This technique is also compatible with the constraint format specified in Table I.

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 nonempty (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 to identify 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 works outward from the MSS. As each grid-coupled VSC will be assigned an area to compensate, it is necessary to continue until the number of segments is equal to the number of VSCs (or twice that in the case of the SSSC). If more areas than this are found, a subset is chosen according to the amount of customer load affected by the compensator, giving the greatest benefit for postfault resupply. Areas are then paired (for point-to-point compensators) or grouped (for MT 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.

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 ensures that unnecessary upgrades are avoided and therefore results in a better comparison between schemes.

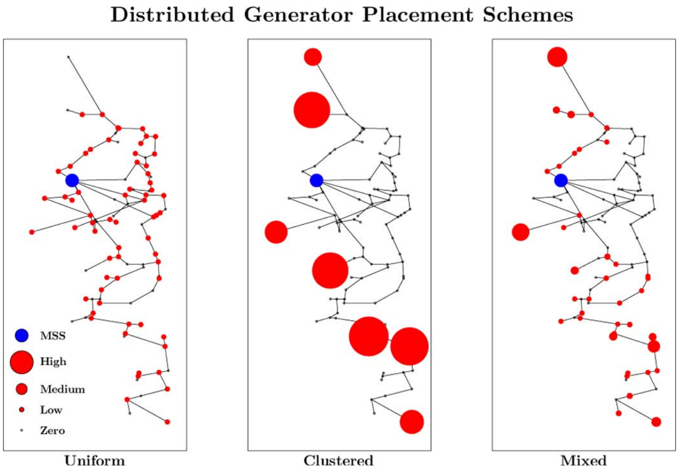


Fig. 2. Topology of one network under study, and illustration of different DG placement schemes.

4) DG 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 representing a large number of small 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. Results presented in this paper are considered for *Mixed Placement* only, but can be scaled according to Fig. 3 to give an idea of how the other two placement scenarios affect the results.

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 greatest marginal benefit is chosen.

The following symbols will be used when presenting results:

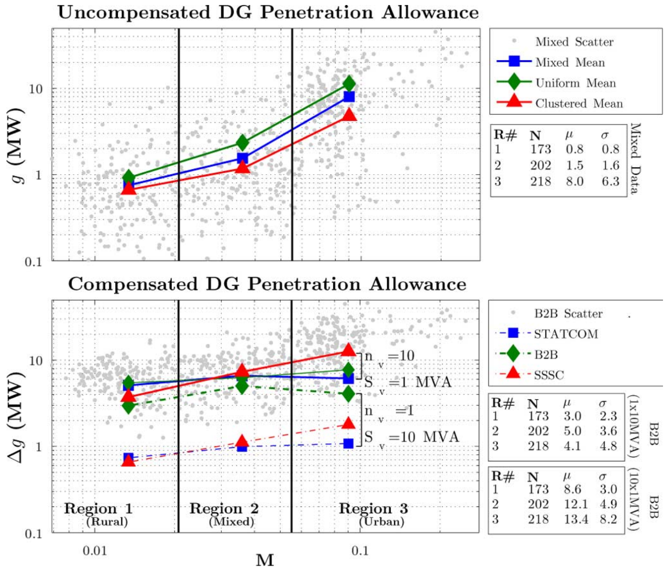


Fig. 3. Allowable DG correlation versus classification metric.

$g, \bar{g}, G$	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 $[kA - km]$;
σ^2	variance in uniform placement results;
Δx	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	sample population used in the presented study and the metric used for subcategorizing this population.

Section IV-A will discuss how to interpret the mean and variance figures presented in Section V. Section IV-B first considers Δg (benefits arising from compensation) for uniform deployment with an untouched infrastructure, that is, 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 (ρ) until the following metric M was found to have the best correlation $(\rho = 0.65)$

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

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 kilometers, and A_i is the rating of the feeder in kiloamperes. 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).

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. Region 1 (low M) represents the rural, Region 2 (medium M) the mixed, and Region 3 (high M) the urban network subsets. This division reduces the sensitivity to outliers and ensures that mean values are taken for similarly sized subpopulations when forming a trend line.

With this classification scheme, urban networks tend to support larger absolute quantities of DG, but with greater variance. In addition, clustered DG placement enables the lowest levels of DG and uniform placement at 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 among several circuits.

Correlation of M with the incremental benefit, Δg (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. The exception to this is found with the SSSC, which is more sensitive to the network type as described in Section II.

The slopes of the subset mean values are used to describe the sensitivity of Δg to variations in M. Table II shows sensitivities for several scenarios. It is observed that the STATCOM varies negatively with M, suggesting that this device is slightly more suited to rural networks. Δg 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 Δg.

While this paper presents a nonparametric statistical study, it is useful to know how the samples are distributed when interpreting the mean (μ) and variance (σ^2) figures presented. Fig. 4 shows a histogram of Δg for a $n_v = 6$. The histogram suggests a skewed probability distribution, and the gamma distribution was chosen as it was able to most closely fit the largest number of

TABLE II
SENSITIVITY OF RESULTS TO NETWORK TYPE

$\mathbf{S_V}$	$\mathbf{n_v}$	*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

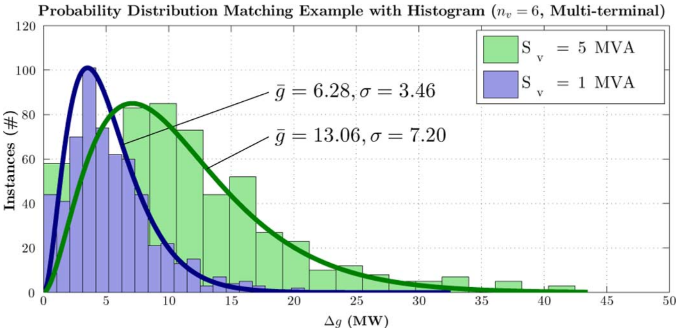


Fig. 4. Histogram with scaled and fitted gamma probability distribution of $\triangle g$.

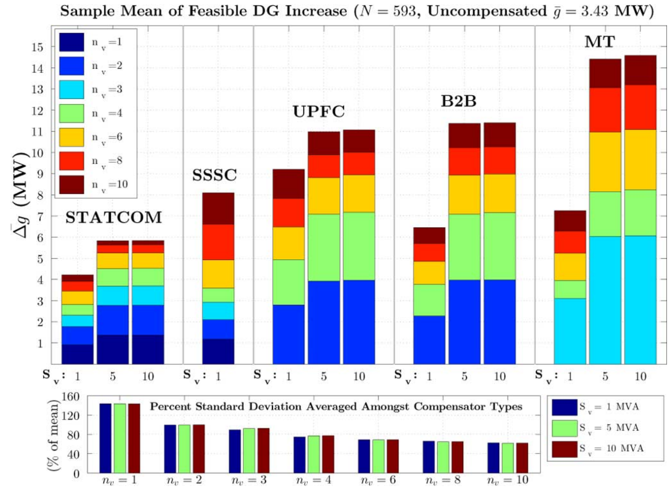


Fig. 5. Results of marginal increases in allowable DG penetration with compensation and summary of variance.

scenarios. A trimmed μ was used as the measure of central tendency due to the presence of closed-form expressions relating μ and σ^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, for example, $G = N \cdot \bar{\Delta g}$. 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.)

TABLE III
COMPETITION TABLE FOR SELECT COMPENSATION SCHEMES

P (A > B) / P (A < B)					
A vs B	$\mathbf{S_V}$	$\mathbf{n}_v = 1$	$\mathbf{n}_v = 2$	$\mathbf{n}_v = 4$	$\mathbf{n}_v = 6$
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

B. Uniform Deployment of Compensators

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

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

Some additional observations are as follows.

- UPFCs and SSSCs with low S_V perform better than back-to-back converters of equivalent rating.
- The multiterminal option performs 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 the converter rating.

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, that is, 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.

C. Infrastructure Upgrades and Compensation Combined

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

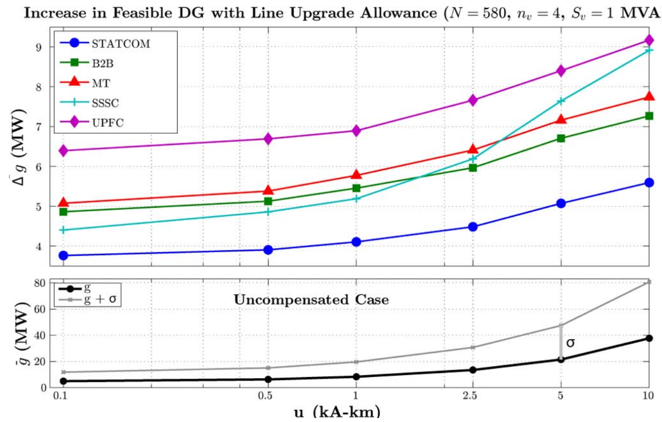


Fig. 6. Allowed DG with increasing line upgrade allowances.

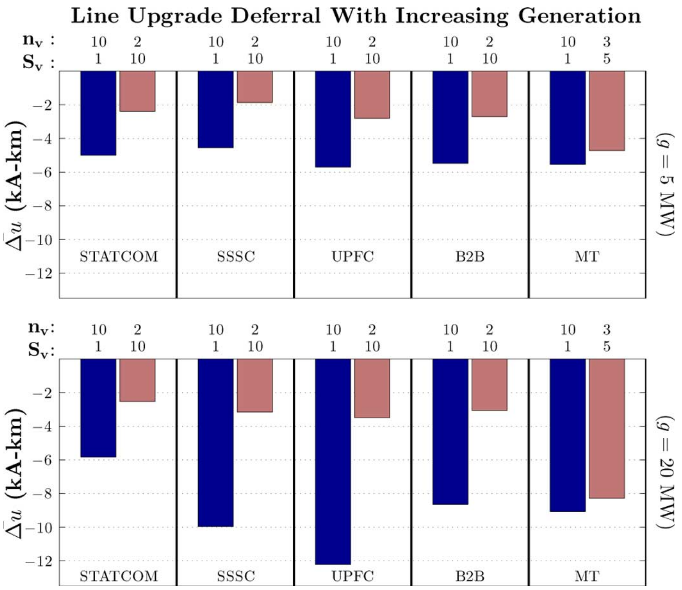


Fig. 7. Feeder upgrades avoided with the use of compensation for different levels of installed DG. For the uncompensated cases at $g = 5$ MW, $u \approx 6.1$ ($\sigma \approx 8.4$) kA-km and for $g = 20$ MW, $u \approx 20.1$ ($\sigma \approx 22.7$) kA-km.

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

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 is shown in Fig. 7. The selected results also compare a small number of 10-MVA compensators and a large number of 1-MVA compensators. In the case of the multiterminal 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., 10×1-MVA units would require additional installation sites but have a lower $n_V \cdot S_V$ product than the 2×10-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 $\Delta\bar{u}$ are similar to that of Fig. 5 with approximately 20 kA-km required for uncompensated networks. The 5xUPFC configuration (10×1 MVA VSCs) offers the greatest decrease in upgrades. This suggests 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 defer costs.

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 that the DNO to upgrade the network as needed. 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. 8(a) shows the resulting ΔG versus N_V with incremental deployment. Also shown is the point resulting from uniform deployment, with four 5-MVA VSCs in multiterminal configuration (x) and four 1-MVA compensators in paired UPFC configuration $(*)$ installed in every network. The results show a much greater overall benefit for a given N_V in comparison with applying the same scheme to all

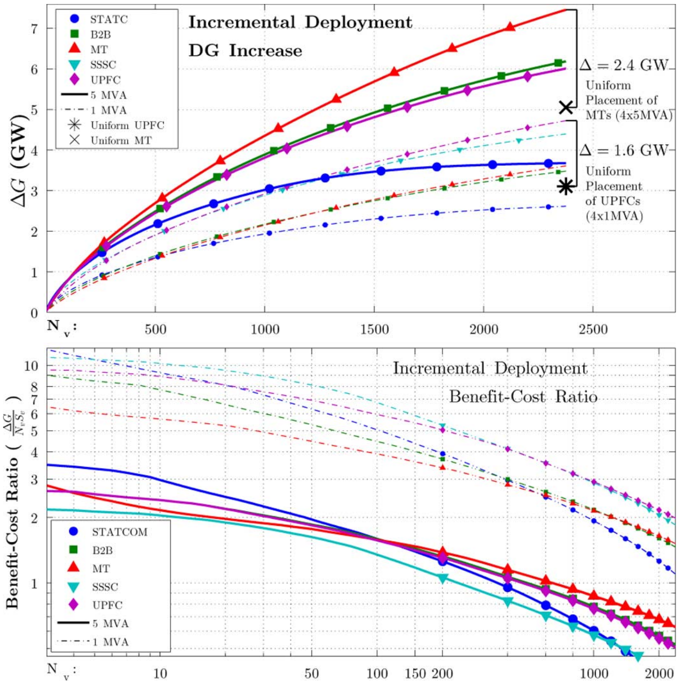


Fig. 8. Total ΔG and benefit-cost ratio for the incremental deployment of compensators.

networks, with a difference of 2.4 GW and 1.6 GW across all networks for the example cases shown in this figure.

Another measure of performance is the benefit-cost ratio $\Delta G/N_V \cdot S_V$ versus N_V (shown in the lower plot of Fig. 8(a) 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 $\triangle g$ tends be with the first device installation. STATCOMs and SSSCs utilize a single VSC to provide compensation and, therefore, this initial large Δg can be applied to 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 STATCOM benefits are reduced if working alongside existing OLTCs, since both 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.

V. Conclusion

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 population consisted of data from nearly 600 U.K. distribution networks. Varying ratings and quantities of shunt, series, back-to-back, and multiterminal compensators 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 to correlate well with this metric, while the marginal DG capacities afforded by compensation are not as strongly correlated (series-only devices excluded). Since marginal benefits are less sensitive to the 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 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 multiterminal compensator offers the greatest flexibility. The back-to-back compensator offers only slightly better performance than the UPFC at higher ratings, but has the additional 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 than 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 smaller cost and dimensions than multiterminal or back-to-back compensators.

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