Evaluation of DC Links on Dense-Load Urban Distribution Networks

Damian Sciano, *Member, IEEE*, Ashhar Raza, Reynaldo Salcedo, *Student Member, IEEE*, Marc Diaz-Aguilo, Resk Ebrahem Uosef, *Member, IEEE*, Dariusz Czarkowski, *Member, IEEE*, and Francisco de León, *Fellow, IEEE*

***Abstract*—This paper presents an investigation of utilizing dc links to merge heavily meshed urban distribution networks in dense-load areas to increase reliability and expand operational flexibility. It provides a cost-benefit evaluation of utilizing dc-link technology to interconnect three segments of New York City electric distribution networks with complex grid configurations. The outcome of this work highlights the advantages provided by dc links, such as increased reliability and power quality, improved voltage support, and demand relief for feeders at or above capacity limitations. Furthermore, the study shows that dc links may provide a better alternative to transformer installations, feeder upgrades, and/or capacitor additions, and offer the opportunity to postpone large capital investments for system upgrades (such as building a new substation) due to demand increase. The study was carried out with power-flow simulations using field-validated power-flow data.**

***Index Terms*—DC links, demand relief, distribution networks, electric distribution grids, electric mesh networks, interconnection, load relief, low-voltage secondary networks, voltage support.**

I. Introduction

METROPOLITAN distribution networks can be extremely large and complex systems due to the large electric power demand and the strict requirements of electrical power quality and reliability. To increase service continuity, urban networks are often designed with the low voltage (LV) secondary side interconnected and forming a heavily-meshed grid. This configuration offers high reliability at the expense of redundancy which contrasts with a radial distribution configuration that is lower cost but cannot provide the level of reliability required for large cities [1].

Two challenges currently faced by utilities are the aging of infrastructure and the increasing power demands of customers. Despite gains in equipment efficiencies, the overall energy usage continues to grow, on average, at a rate of approximately 0.9% per year [2]. Yearly maintenance cost increases and expansion in highly utilized urban streets becomes ever more difficult to manage demand growth. Replacing thousands of miles of existing cables is impractical and uneconomical. Instead, a smart, coordinated, and targeted approach to grid maintenance and enhancement becomes critical to utility survival [3].

In addition, utilities are considering the implementation of distributed energy resources (DER) [4], improved SCADA [3], and smart grid self-healing technologies such as switches to sectionalize the distribution network under contingency conditions without drastically increasing costs [5], [6]. All these techniques, however, are difficult and/or costly to implement. Utilities typically have limited influence over customer sizing and location of distributed generation (DG) making it difficult to exploit these technologies in the planning process. Possible SCADA solutions typically require large scale, high cost investments such as upgrading to smart meters and building the required information technology to support it [5]. The incorporation of self-healing principles using automatic reconfiguration (often via switches) offers optimality during contingencies [6]. However, this approach is limited to contingency operations and may require momentary outages to critical customers. This paper asserts that another infrastructure upgrade option exists using dc-link technology. dc-links, sometimes referred to as dc-bridges or B2B (back to back) installations, are solid state electronic devices that connect two electrical systems or components and deliver real and reactive power, in either direction, as desired.

A literature review finds proposals for dc-link applications at the distribution level focused on interconnecting synchronous or renewable generators [7], [8]. Other applications for the dc-link are built around facilitating micro-grid architectures [9] that will remain connected to the utility as well as enhancing voltage control and addressing power quality considerations [8], [10]. Two papers propose interconnecting medium voltage feeders on dissimilar systems [11], [12]. There is also an instance in the NYC distribution system where a dc-link was utilized to test the feasibility of interconnecting an emergency generator into the electric distribution system [13], [14]. There are no published works discovered proposing dc-links to intertie two adjacent networks in a densely populated urban area; nor publications found where dc-links are used between secondary networks (or creating the optionality to move between primary and secondary network connections).

Manuscript received April 07, 2015; revised September 10, 2015; accepted December 17, 2015. Date of publication December 25, 2015; date of current version May 20, 2016. Paper no. TPWRD-00439-2015.

D. Sciano and R. E. Uosef are with Consolidated Edison Inc., New York, NY 10003 USA (e-mail: scianod@coned.com; uosefr@coned.com).

A. Raza, M. Diaz-Aguilo, D. Czarkowski, and F. de León are with the Department of Electrical and Computer Engineering, New York University Polytechnic School of Engineering, Brooklyn, NY 11201 USA (e-mail: ashhar.raza@nyu.edu; maguilo@nyu.edu; dc1677@nyu.edu; fdeleon@nyu.edu).

R. Salcedo was with the Department of Electrical and Computer Engineering at New York University, New York, NY 11201 USA. He is now with the Massachusetts Institute of Technology Lincoln Laboratory (e-mail: rsalcedo@mit.ll.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2015.2512610

At the transmission level, however, there are significant and growing examples of using high voltage direct current (HVDC) transmission to move large amounts of power between disparate transmission systems [15]. The examples of HVDC systems inspired the authors to study the potential benefits of inter-tying portions of dissimilar networks via dc-links.

This paper presents for the first time an investigation on dc-links to intertie heavily-meshed urban distribution networks in dense load areas. If implemented correctly, the dc-links can replace a portfolio of traditional network design improvements (i.e., adding transformers, upgrading feeders and incorporating switches) while also helping to defer the large cost of a new substation, enabling conservation voltage optimization (CVO) programs and providing injection points into the grid that will encourage renewable energy and battery storage. Furthermore, it provides a cost-benefit evaluation of the dc-link technology considering its implementation to interconnect various portions of actual electric networks with complex configurations. This feasibility study is performed with power flow simulations using a field validated computer program.

II. Description of the Proposed Methodology

Improvements in solid state technologies are creating opportunities to enhance the existing electric system. For decades, High Voltage Direct Current (HVDC) links have been used at the transmission level to bridge different power angles and frequencies in power systems [15]. At medium voltage (MV) and low voltage (LV) levels, similar IGBT solid state technology referred to as dc-links (ac-dc-ac conversion) is being developed to provide uninterrupted power supply and to facilitate the interconnection of distributed generators to utility grids [7], [8]. Renewable generation such as wind and solar, also use similar type of inverter based technology to connect to the electric grid [7]. All these applications continue to drive performance improvements in solid-state technology. This paper explores the application of dc-links to join various portions of urban electric systems offering efficient real and reactive power sharing capabilities (MW and Mvar), which could provide enhanced reliability, operational flexibility to address system needs, and voltage support for both high load and low load periods.

Electric distribution systems in urban areas are built almost exclusively based on the central plant design model which delivers power from large power plants, via transmission lines, into urban areas where it is distributed to customers of various sizes and load profiles. Typical electric distribution networks have three components: (1) an area substation that converts transmission power to “primary” or “medium” voltage; (2) “primary” or “medium” voltage feeders (typically 15 kV to 35 kV); (3) network transformers to step down the voltage and (4) “secondary” mains that deliver customer level voltage (120/208 V in NYC and many other systems). Distribution systems are considered to be networked if either the primary and/or secondary cables are inter-tied. Fig. 1 illustrates a distribution system with radial primary feeders and a heavily-meshed secondary network, which is a typical configuration used by Con Edison [6]. Due to the age of many of these systems, the designs are not usually made to accommodate or benefit

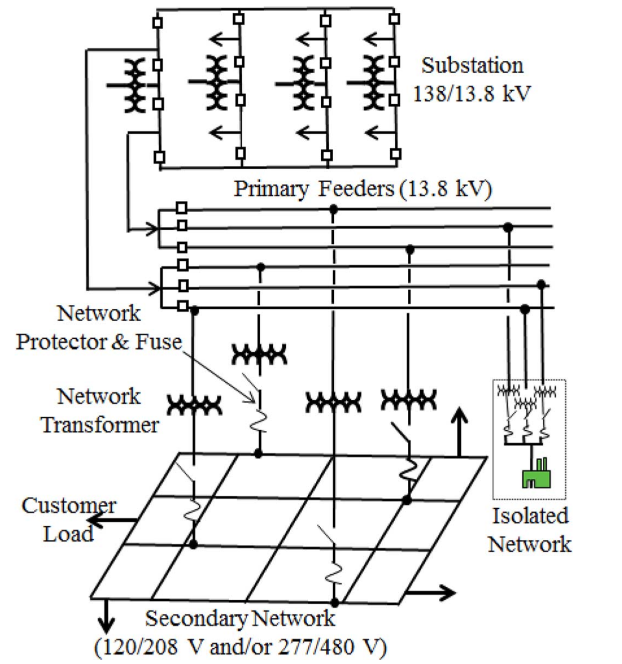

Fig. 1. Typical configuration of NYC distribution networks (radial primary with meshed secondary grid).

from Distributed Energy Resources (DER) such as renewables, distributed generation and battery storage which are relatively new technologies [3]. The network in Fig. 1 achieves reliability through a combination of redundancy at the substation and a dense secondary grid. Over time, distribution systems have been progressively expanded to meet the increasing demand for reliable power by building redundancy into the system and employing a large fleet of vehicles and personnel to respond quickly to maintenance needs [6], [16], [17]. This type of system is becoming increasingly costly to service, maintain and grow to meet new customer loads.

A. Interconnecting Distribution Systems Through DC-Links

In large cities, the electrical distribution systems are subdivided into discrete networks built in proximity to each other reliably serving the load [17]. These systems are costly because they are built underground and compete for space with multiple other utilities (sewer, water, telecom, natural gas, etc). New substations in urban areas are particularly costly because of the high cost of acquiring the properties and restrictive zoning requirements. Based on the yearly peak load forecasts, utility engineers attempt to re-configure their system components to remain below full capacity [18] during peak load conditions and worst case contingencies to avoid the high cost of adding new components in the streets and ultimately to delay the need for new and costly substations. Disparate load growth in different networks results in some networks reaching their design limits sooner than adjacent networks. Having a means of “sharing” the added capacity of one network with another network would delay costly substation and other infrastructure builds thus saving money.

Unfortunately, this “sharing” between networks cannot be accomplished with switches for two primary reasons: increase in

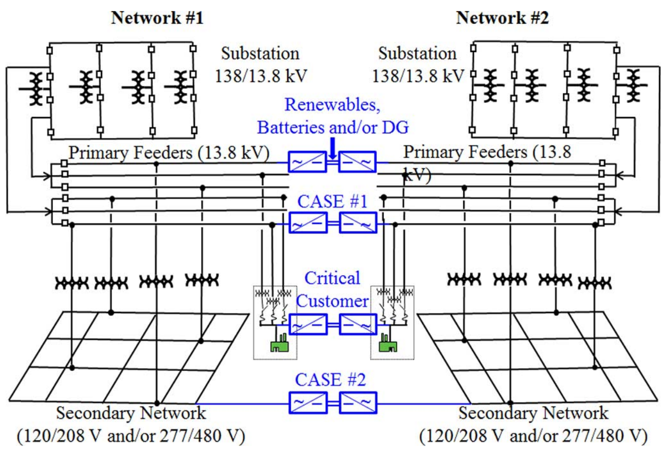

Fig. 2. Potential dc-link interconnections in existing distribution architecture including Case #1 and Case #2 injection points.

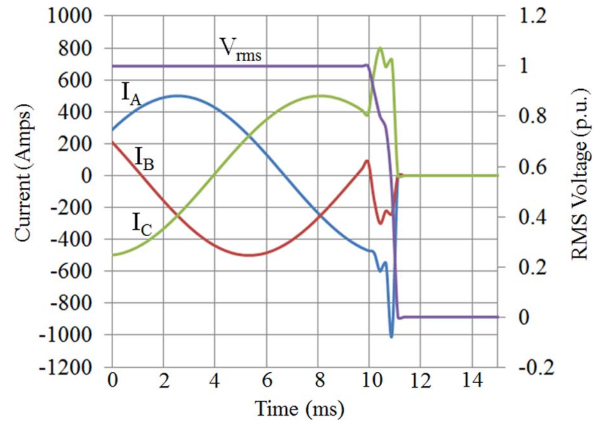

Fig. 3. Field test: current through dc-link during a three-phase bolted short circuit. The dc-link voltage threshold was set at 50% for this test [13].

fault current and phase angle difference. However, the non-synchronous aspect of the dc-link allows for the bridging of angle differences and the fast power electronics can be used to interrupt or mitigate the undesired fault currents [13]. In addition, the nature of the dc-link allows active power and/or reactive power to flow from one network to the other so both networks can benefit from the interconnection.

Fig. 2 illustrates some of the proposed uses of the dc-link. The intertie could be at the primary feeder level with typical units ranging from 2 MW to 10 MW or at the secondary level with typical units ranging from 100 kW to 2 MW. Applications could include: (1) shifting load from overloaded feeders in one network to feeders with added capacity in another (studied in case #1); (2) providing voltage support by adding reactive power during peak loads and absorbing reactive power during light loads (studied in case #2); (3) providing more reliable service to critical customers via two separate networks and; (4) enabling injection of power from emergency vehicles or from nearby dc sources such as photovoltaic panels or battery storage. This can be designed to avoid reverse power flow that is sometimes the unintended consequence of customer sited photovoltaics that jeopardize the reliability of the grid [19].

The advantages of interconnecting electric systems using dc-links are not restricted to urban networks. Though not studied here, radial distribution systems may also realize notable benefits from this technology such as increased redundancy and a resultant improvement to reliability.

B. Benefits of DC-Links to Inter-Tie Distribution Networks

The dc-link was chosen because of its speed of operation (i.e., fractions of a 60 Hz cycle) and its ability to deliver power at any given power factor and in either direction. The fast power electronic switches provide the ability to disconnect the systems in relatively small time windows; generally a half cycle or less [14]. This eliminates the concern of increasing fault currents or migrating power interruptions when connecting networks. Fig. 3 displays the fault interruption capability measured during field tests of a dc-link. A 2 MW synchronous generator was used to supply power to a load bank via the dc-link. The dc-link was set to interrupt a fault at a voltage threshold of 50% and a three-phase bolted fault was then placed on the output of the dc-link to evaluate the fault current limiting capabilities [13]. The dc-link interrupted the fault in less than a quarter cycle and kept the fault current to below 2 per unit during this time period. This is dramatically better than conventional breakers or switches which require a minimum of 3 to 5 cycles to interrupt a fault fed by synchronous generators that might reach 7 to 10 per unit.

Moreover, phasing of the current flow can be applied such that any combination of reactive power can be supplied to both networks (i.e., lagging power to both networks or leading power to both networks or leading power to one network and lagging power to the other) [9]. This is similar to having a Distribution Static Synchronous Compensator (D-STATCOM) placed in each network. Thus, the most important limitation to power transfer would be the rated size of the power electronics equipment. These key factors highlight the portfolio of benefits dc-links provide over transformers, capacitors and the use of self-healing switches, especially since switches must remain in a disconnected (or open) position until a contingency occurs and cannot clear quickly enough to mitigate fault currents. This paper investigates whether the implementation of the proposed approach offers economic advantages by alleviating in-service equipment and eliminating the need for new installation of transformers and capacitors to satisfy demand growth. The current efficiency of the dc-link is in the 98% range [13] and is approaching the efficiency of a transformer (roughly 99%) so the conversion ratio is also satisfactory.

DC-links facilitate the use of available capacity in adjacent networks that would otherwise remain unused. This can delay the need to build a costly substation and can also provide the reactive power support to enable programs like conservation voltage optimization (CVO) that would otherwise be prevented by low voltage conditions on the fringes or edges of the network.

III. Distribution Systems Under Study

To properly evaluate the technical and economic benefits of dc-links in urban distribution systems, three adjacent heavily meshed networks were selected. The selection process was comprised of: 1) analyzing the load relief and reinforcement program of the utility to identify networks requiring enhancements

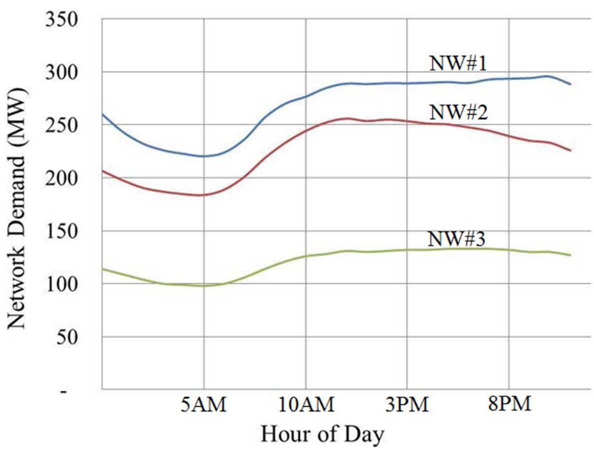

Fig. 4. Peak demand load profiles of the distribution networks under study.

TABLE I
PEAK LOADING CONDITIONS OF THE NETWORKS

Parameter	Units	Nwt-1	Nwt-2	Nwt-3
MV Feeders	kV	13.8	13.8	13.8
LV Network	V	120/208	120/208	120/208
Peak active power demand	MW	275	238	128
Peak reactive power demand	Mvar	149	122	50
Power factor	-	0.88 (lag)	0.89 (lag)	0.93 (lag)
Line charging	Mvar	11	3.0	4
Shunt capacitors	Mvar	80	60	20
Shunt Reactors	Mvar	0	0	0

TABLE II
ELEMENTS OF THE NETWORKS

Network Element	Nwt-1	Nwt-2	Nwt-3
Substation transformers	4	5	4
Shunt capacitors	4	3	1
Substation breakers	16	18	18
MV feeders	29	28	24
MV feeder breakers	29	28	24
MV feeder sections	4,869	1,791	1,671
Network transformers	538	419	301
Network protectors	538	419	301
Secondary mains	7,523	4,373	6,239
Customers Served (approx)	80,000	44,000	38,000

in the form of new feeder or service transformers; 2) identifying regions with poor reliability and power quality; and 3) investigation of load profiles for dense-load areas to determine opportunities between adjacent networks having non-coincidental maximum loads during the day.

The search resulted in the selection of three neighboring networks (for security and privacy purposes referred to as network-1, network-2 and network-3) representing an area subset of the NYC distribution system having different load profiles, voltage problems and issues regarding feeder capacity limits. For example, network-1 is fed from a substation that is already at capacity and is located on the other side of the river. Thus, the cost of adding new feeders is extremely high in network-1 and thus alternative solutions are desirable.

The basic architecture of these networks is illustrated in Figs. 1 and 2 and is described in [4], and [20]. The networks are fed by a double syn-bus type substation via radial, medium voltage feeders that are rated at 13.8 kV, 27 kV, or 33 kV. The medium voltage feeders supply network transformers which step this voltage down to 120/208 V for delivery to customers via low voltage mains and services. A summary of electrical demand of each network is given in Table I and Fig. 4 displays the peak hourly demand load profiles of the selected systems and is a good gauge of the utilization of each networks substation, feeders and transformers. Table II shows the quantity of electrical components being modeled in the three networks under review. Network-1 is predominantly a residential area with limited commercial load. As a result, network-1 peaks after work hours. The substation supplying network-1 is near maximum capacity, requiring immediate demand support and potentially the need to build a new substation. Furthermore, this network has several low voltage zones at the fringes (i.e., the downstream edges) and this also increases concerns for a new substation and limits the opportunity to institute a CVO program, which achieves a slight voltage reduction in the entire network by lowering the voltage at the substation.

Network-2 is more heavily composed of commercial loads with a peak demand during typical work hours and lower demand after 5 PM. Network-3 is a residential area with a relatively new substation which may be leveraged to alleviate the need for active power in network-1. These networks are geographically next to each other facilitating the connection of fringes and MV feeders by dc-links. Fig. 2 displays where the dc-link connections are made.

IV. PERFORMANCE EVALUATION

This section is devoted to the evaluation of dc-links intending to reduce possible voltage violations on geographical zones with low voltages, and to provide demand relief to distribution systems reaching capacity limits. The distribution system selection process discussed in Section III revealed that because of geographical proximity and relatively low loading on network-3, opportunities exist to transfer electric power from network-3 into network-1 via a dc-link. This would avoid costly feeder builds and consequently, defer the required capital investments of building a new substation to relieve network-1. In addition, the intertie between network-1 and network-2 presents significant voltage support needs at the outer edges of network-1. Fig. 5 illustrates how voltage can drop below the required 0.95 p.u. (lower left hand corner) under the worst case when two medium voltage feeders are lost. Each point in Fig. 5 represents a geographical position of the load with x and y axes representing the x and y co-ordinates respectively. The loads are shaded according to its position on color bar corresponding to its voltage. Case #2 (below) utilizes a dc-link to resolve the voltage violation problems.

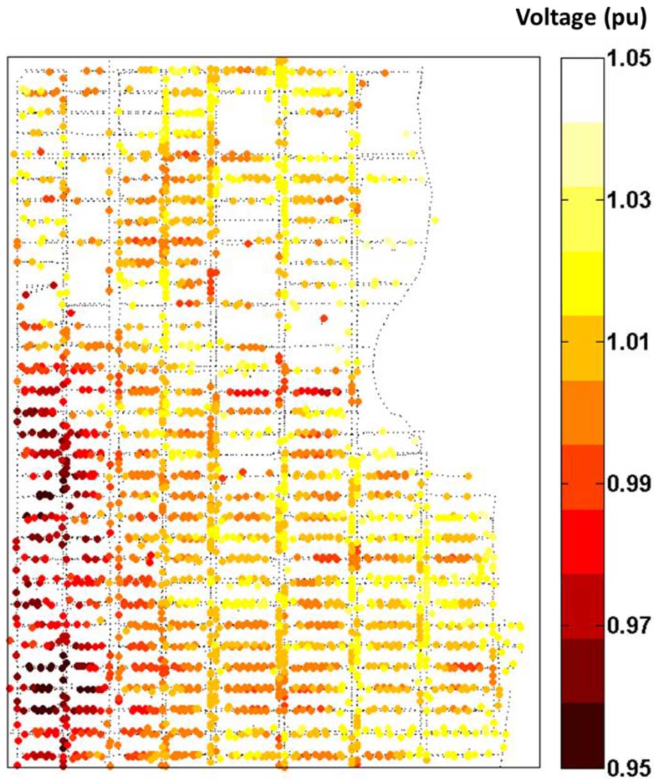

Fig. 5. Voltage profile of secondary terminals of network transformer for network-1 during contingency without dc-link installations.

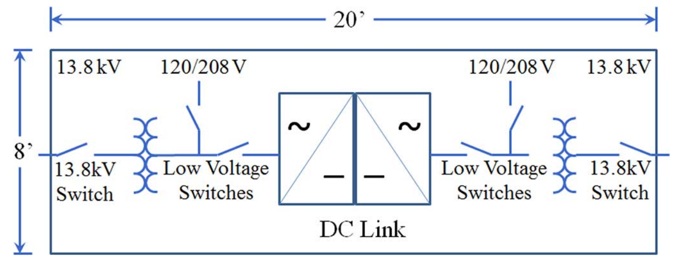

Fig. 6. Proposed dc-link configuration to enable MV and LV connection.

A. Modeling and Selection of the DC-Links

A 2 MVA dc-link was selected to perform the studies. This dc-link size is roughly equivalent to a large network transformer. 2 MVA also represents a practical limit of how much power can be delivered on the 120/208 volt secondary system while also being a meaningful amount of power to alleviate overloads on the 13.8 kV primary feeders. The dc-link is capable of supplying any combination of MVAR and MW up to a total of 2 MVA. In addition, the dc-link may be configured to bilaterally supply reactive power support to both of its terminals. For the presented scenarios, the dc-link was modeled with 2 MVA at a power factor of 0.90 (Case #1) and 2 MVA at a power factor of 0.30 and 0.40 (Case #2). To determine the effect of the dc-link through power flow analysis the dc-link is modeled as a load for the sending end and as a generator for the receiving end. The power factor of both of these units was maintained according to the desired mode of operation. This load and generator model was then inserted into the validated network model developed in OpenDSS. Details of the model are presented in [23].

The IGBT technology on the dc-link is well suited for 600 V or below and requires transformation to be used on primary feeders. This implies that dc-links may be more economical when implemented at the LV network level. Practically speaking, though, the cost of this transformation is relatively small and the optionality of being able to connect to either the secondary or primary voltages (or both) should outweigh this cost. Hence, the setup shown in Fig. 6 is presented as the design case for the dc-link. This paper compares the reliability benefits of tying distribution networks via the dc-links at both LV and MV levels.

dc-links typically have robust control and communication capabilities which can be programmed via human machine interfaces (HMI) and accessed remotely. It is anticipated that for the cases studied, the controls will be set to send real power from one feeder to the other when one feeders loading exceeds 90% as determined by the dc-link communicating with the Energy Management System (EMS). Sensors for this data would be located at the substation. Software can then notify the operator who can chose to override this control. In the case of voltage control, the dc-link can be set to provide reactive power as needed to maintain a preset voltage range.

Based on actual field measurements, this paper assumes the fault clearing time of the dc-link is short (Fig. 3), and thus, the transient fault contribution to the systems is negligible [14]. Thus, the studies presented in this paper are dedicated to evaluating the steady-state performance of the dc-link installation connected to both networks. Future work may include the evaluation of the fault clearing threshold settings and other transient considerations.

B. Case#1-Application of DC-Link to Provide Demand Support

A review of the 2015 peak load forecast for network-1 was made and it was found that 22 of 29 feeders had sections that were forecasted to be loaded at 90% or above during pre-contingency, peak conditions; of those 22 feeders, 3 had sections loaded over 100% of rating, and 13 feeders had sections loaded over 95%. In addition, this particular network is forecasted to see load growth in the 10% range within 3 years because of energy intensive projects that are already underway. There is limited capacity at the substation and any efforts to utilize this capacity via feeders will require costly river crossings because of the location of the substation for network-1. Adjacent network-3 was recently built and has extensive excess capacity at both the substation and in the 24 feeders. Many of network-1 and network-3 feeders share common duct runs which will help facilitate inter-tying a dc-link to both networks and keep the connection costs low.

In this scenario, the dc-link was intertied between a feeder on network-1 with six sections having pre-contingency loading of 101% and a feeder on network-3 that had a maximum loading below 60% on all feeder sections. The intertie was created near the seam of network-1 and network-3 at the 128$^{\mathrm{th}}$ section of the network-1 feeder and at the 64$^{\mathrm{th}}$ section of the network-3 feeder. Fig. 7, shows the feeder loading (in % of capacity) for

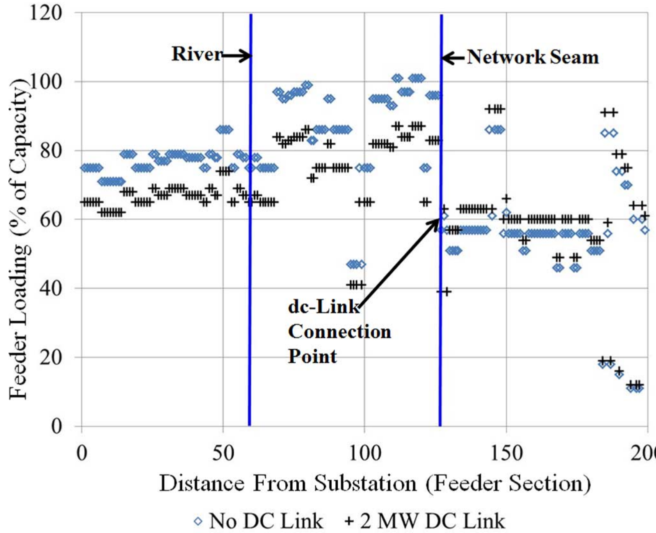

Fig. 7. Loading on selected feeder (in % versus feeder section) for network-1; before (no dc-link) and after (2 MVA dc-link) dc-link interconnection.

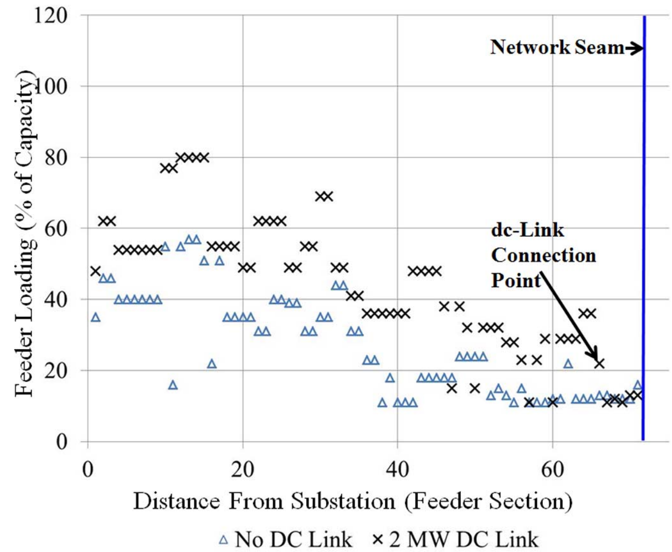

Fig. 8. Loading on selected feeder (in % versus feeder section) for network-3; before (no dc-link) and after (2 MVA dc-link) dc-link interconnection.

TABLE III
CASE #1: KEY BENEFITS OF DC-LINK AT DE-LOADING MV FEEDERS

Sections loaded over 100% without dc-link	6
Sections loaded over 100% with dc-link	0
Highest section loading without dc-link	101%
Highest section loading with dc-link	92%

feeder sections as they emanate out from the substation (for example, section 1 is nearest to the substation and section 200 is farthest out from the substation in Fig. 7). The dc-link connection point de-loads the feeder between sections 1 and 127 which is where the forecasted overloads existed. The sections that were previously loaded above 100% (shown as diamonds in Fig. 7.) dropped to between 80% and 90% (shown as crosses in Fig. 7.) displaying a clear benefit to utilizing the dc-link. Table III summarizes these results. Due to the dc-link changing the phase angle of the feeder with respect to the rest of the network, downstream loading on the feeder (i.e., sections 129 to 200) increased slightly but remained within acceptable ranges.

Fig. 8 displays the "host" feeder from network-3 that provides the MVA to de-load the feeder in network-1 as a function of section loading (in % of capacity) versus feeder section. Prior to intertie with network-1, this feeder had maximum section loading under 60% as can be seen from the triangles in Fig. 8. After the dc-link connection, this feeder loading increased to as high as 80% but well below its normal rating as can be seen from the "x" characters in Fig. 8. This arrangement allowed the deferral of building new feeders to network-1 that included the added costs of running them under a river. This is captured in the cost benefit analysis in Section V.

C. Case#2-Application of DC-Link to Improve Voltage Profiles

As previously displayed in Fig. 5, the fringes of network-1 have shown under-voltage concerns. Creating an intertie between network-1 and network-2 would present significant

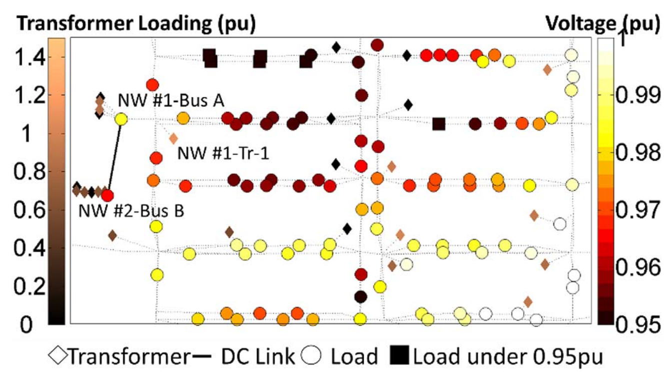

Fig. 9. Voltage profile of loads and transformer loading near the dc-link injection point during peak conditions and N − 2 contingency.

voltage support improving voltage quality in the area. This scenario analyzes the voltage enhancements of network-1 under contingency before and after its connection to network-2 for voltage support. The study was restricted to the region with worst case under voltage conditions shown in Fig. 5 and subjected to "N − 2" design which means the system can lose the largest two components and still meet peak demand. For the study the two most impactful feeders to the voltage on and around the fringe of network-1 were taken out of service. The simulations consider the possibility of implementing the dc-link on the LV secondary grid at 120/208 V level. Fig. 9 illustrates the voltages of the loads in the south west region of the network-1 under worst double contingency scenario at peak loading. Network-1 bus A (NW#1-BusA) is the site selected for dc-link connection in network-1 and network-2 bus B (NW#2-BusB) is the site designated for connecting the dc-link in network-2. N–2 contingency scenario takes 9 transformers out of service thereby producing a low voltage scenario in the region where several loads are under 0.95 per unit as shown in Fig. 9. Also, network-1, transformer 1 (NW#1-TR1) is overloaded to 110% under this contingency.

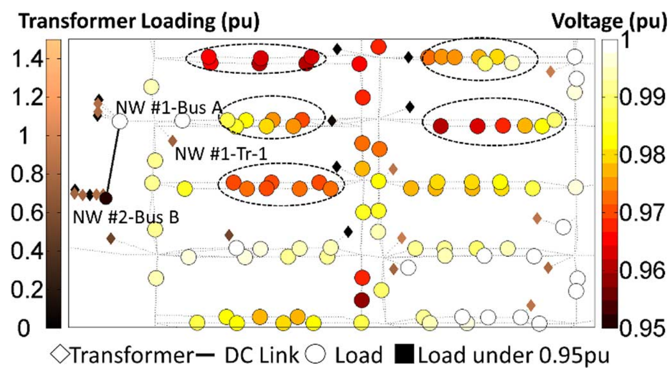

Fig. 10. Voltage profile of loads and transformer loading with a 2 MVA 0.3 pf dc-link; same conditions as in Fig. 9.

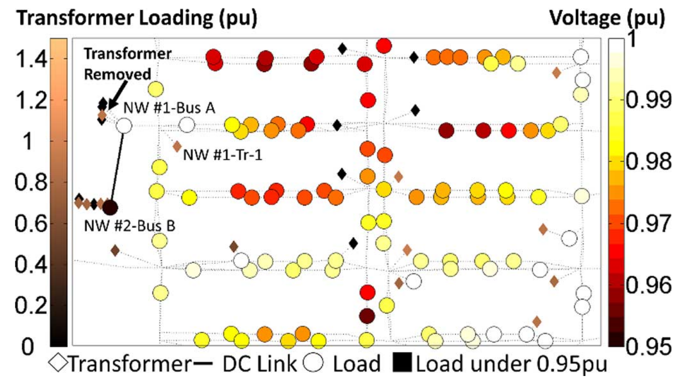

Fig. 11. Voltage profile of loads and transformer loading with a 2 MVA and 0.4 power factor dc-link.

TABLE IV
CASE #2: KEY BENEFITS OF DC-LINK AT LV UNDER N − 2 CONTINGENCY

Number of loads below 114 V without dc-link	6
Number of loads below 114 V with dc-link	0
Numbers of loads with 2 volt or more increment after dc-link	15
Loading at NW #1- Tr1 without dc-link	1.1 pu
Loading at NW #1- Tr1 with dc-link	0.75 pu
Number of transformers with more than 5% reduction in Loading after dc-link	4

A dc-link between network-1 and network-2 connected at NW#1-BusA and NW#2-BusB respectively can improve the voltage profile in region of network-1 without affecting the NW#2-BusB in network-2. In fact, the dc-link is essentially a back to back DSTATCOM and as such, can provide voltage support to both networks simultaneously [9].

Significant voltage rise is seen in the region encircled in Fig. 10 and all the voltage points were raised above the 114 V target voltage. The proposed dc-link is operated at 2 MVA and 0.3 power factor injecting power in network-1. In addition to alleviating under-voltage situations, the dc-link also helps in relieving loading on transformer NW#1-TR1. Loading on NW#1-TR1 reduces from 110% to 74.90%. Therefore it is seen here that the dc-link can improve the voltage profile and relieve transformer overloading under worst double contingency and peak loading situation even when the sending ending is under double contingency.

The results indicate that connecting the dc-link at the LV level provides greater voltage control than when connected to the MV feeders as would be expected since the reactive power is delivered directly to the point of low voltage. This voltage control comes at roughly the same cost as adding a new transformer and achieves a wider range of voltage influence useful not only at peak loads but at low loads (see Fig. 10) as well since there is no reactive power control on the networks. Key benefits achieved with the dc-link under N − 2 contingency are given in Table IV.

D. Improved Reliability

The dc-link improves the reliability of the network since a dc-link is connected to the LV network and will not go out of service and will continue to work satisfactorily even under N − 2 contingency in the sending network as shown in Section C. Four transformers are connected to bus compartment NW#1-BusA in the existing configuration, each rated at 1000 kVA for normal operation. Under double contingency scenario simulated in Section C, 2 of these 4 transformers go out of service. It is seen that with the addition of dc-link, another transformer can be taken out of service permanently and be used elsewhere by the utility, leaving only 3 transformers in service at normal operation and 1 transformer in service under N − 2 contingency. Fig. 11 shows the simulation results.

Voltage at NW#1-BusA under N − 2 contingency before dc-link connection is 118 volts and it rises to 124.1 volts. This rise in voltage of 6 volts cannot be achieved with the addition of another transformer at NW#1-BusA displaying the advantage of utilizing a dc-link over traditional transformers. Loading at Tr-1 in NW#1 is now at 90%.

V. COST-BENEFIT ANALYSIS

Capital programs for distribution utilities typically involve a combination of (1) equipment replacement to maintain reliability by replacing failure prone components; (2) network reinforcement to meet increasing customer demand by adding equipment to the existing network and; (3) new equipment installation to provide service for new customers. In all cases, the equipment being replaced or added is largely composed of feeder sections, new feeders, transformers, and secondary mains. The cost benefit of a dc-link is most appropriately compared to the network reinforcement programs which are broken up as follows and shown in order of increasing costs:

Primary Reinforcement (for medium voltage feeders):

— Shifting load (by moving a transformer) from a heavily loaded feeder to a nearby, more lightly loaded feeder can be one of the most cost effective solutions (least costly).
— Replacing overloaded sections of the feeder with a higher capacity cable. Another option is to run a parallel path to the overloaded feeder section and overtime, multiple sections with parallel paths lay the groundwork for installing a new feeder.
— Installing a new feeder to meet growing customer load is the most expensive primary reinforcement techniques but

is sometimes the only solution as existing feeders approach full utilization (most costly).

— Case #1 looks at using a dc-link to connect medium voltage feeders (13.8 kV) and use the excess capacity in one feeder to relieve loading on the other feeder during peak conditions. It is assumed that one "section" (roughly 250 feet) of medium voltage cable must be run to make this connection.

Secondary Reinforcement (for low voltage networks):

— Replacing overloaded sections on the secondary network is the lower cost solution for secondary reinforcement and buys time before transformation has to be added (least costly).

— Installing new transformers to meet customer load and address low voltage conditions. This is very costly in NYC because of the cost of building an underground vault and network protector (most costly).

— Case #2 looks at using a dc-link to connect two separate low voltage networks (120/208 V) to provide voltage support. The low voltage mains will have to be reinforced (i.e., on average 8 new mains added) to properly handle this additional loading.

To keep costs low, every attempt is made by design engineers to increase the utilization of all the network components before moving to the more costly steps of new feeder installation and transformer additions. Primary and secondary reinforcement programs are also closely tied together since the addition of a single transformer typically requires some feeder reinforcement. Other challenges for design engineers may include the fact that some network transformers are fixed tap design and voltage control is established at the substation so the only way to address low voltage conditions is with transformer replacement, feeder upgrades or the installation of capacitor banks.

Based on the load flow analysis findings, the dc-link can prove to be a better means of addressing voltage and load flow concerns than the traditional solution of adding a transformer or upgrading a feeder (to reduce line loss) because it supplies voltage support to both networks. A net present value (NPV) analysis was performed to determine if the dc-link would also be a cost beneficial solution. The analysis considered the upfront cost of the dc-link (defined as the current value of the dc-link at year 0 or CV_0), the future benefits (FV_t) and the cost of money (r) as displayed in the following equation:

$$NPV = -CV_0 + \sum_{n=1}^{t} \frac{FV_t}{(1+r)^t} \quad (1)$$

Table V displays the assumptions and results of utilizing a dc-link versus traditional methods and uses costs typical of those found in a NYC network.

As can be seen in the Cost Element section of Table V, the cost of the dc-link itself is considerably higher than a transformer (as well as the vault costs because the dc-link is physically larger). However, there are advantages to tying together two networks via MV feeders (Case #1) and/or two networks via LV networks that may be realized in avoiding feeder replacement or the cost of adding a transformer and reinforcing the secondary mains, respectively. Table V displays these savings for both cases and though there is significant upfront cost for utilizing a dc-link (as well as line losses) the NPV of the benefits ultimately outweighs these costs.

TABLE V
COST BENEFIT OF DC-LINK VERSUS TRADITIONAL METHODS

(ALL VALUES ARE IN 000'S)			
Cost Element	**Trans-former**	**dc-link**	**Feeder**
Low Voltage Reinforcement	$ 1,170	$ 780	$ -
Medium Voltage Connection	$ 110	$ 110	$ 5,000
Equipment	$ 80	$ 600	$ -
Equipment Vault (in-ground)	$ 260	$ 430	$ -
Total	$ 1,620	$ 1,920	$ 5,000

Assumptions		
Category	**Value**	**Calculation**
Carrying charge for capital	20%	Deferred Savings
Discount Rate for a typical utility:	10%	Future cash flows
dc-link utilization as a % of rating	55%	Based on utility avg. demand/peak
Transformer efficiency	99.5%	
dc-link efficiency	98.0%	
Incremental losses	1.5%	dc-link losses

COST BENEFIT ANALYSIS #1: UTILIZE DC-LINK TO DEFER NEW FEEDER COSTS IN NETWORK #1				
	Year 0	**Year 1**	**Year 2**	**Year 3**
dc-link	$ (1,920)	$ -	$ -	$ -
Deferred Savings	$ -	$ 1,000	$ 1,000	$ 1,000
dc-link losses	$ -	$ (14)	$ (14)	$ (14)
Total Benefit (Cost)	$ (1,920)	$ 986	$ 986	$ 986
Discounted Cashflow	$ (1,920)	$ 896	$ 815	$ 740
Net Present Value	$ 531			

COST BENEFIT ANALYSIS #2: UTILIZE DC-LINK IN LIEU OF TRANSFORMER(S)				
	Year 0	**Year 1**	**Year 2**	**Year 3**
dc-link	$ (1,920)	$ -	$ -	$ -
Avoid Transf. NW#1	$ 1,620	$ -	$ -	$ -
Avoid Transf. NW#2	$ -	$ -	$ -	$ 1,620
dc-link losses	$ -	$ (14)	$ (14)	$ (14)
Total Benefit (Cost)	$ (300)	$ (14)	$ (14)	$ 1,606
Discounted Cashflow	$ (300)	$ (13)	$ (12)	$ 1,206
Net Present Value	$ 881			

The "Assumptions" section of Table V describes the parameters used in the NPV calculation:

— The Carrying charge for capital reflects deferred savings obtained by postponing capital outlays (such as an MV feeder in Case #1). The 20% cost is typical for utility equipment and includes interest, taxes, and maintenance.

— The discount rate, r, for a typical utility is the weighted average cost of capital for a utility and it a combination of a utilities cost of equity and debt (used for Case #1 and #2).

— The dc-link utilization is important because it reflects the amount of use the dc-link will see with respect to its full capacity; the more use, the lower the cost of deploying the dc-link. In this case, the overall system utilization rate for a NYC network was used (used for Case #1 and #2).

— Finally, the transformer efficiency and dc-link efficiency where needed to determine the net (used for Case #1 and #2).

For Case #1, the dc-link may be used to take advantage of a lower utilized network; network-3 in this case. (It should be noted that as long as the networks selected have different peak hours, it will be possible to utilize the dc-link even in two equally subscribed networks.) In cases like network-1 where expensive river crossings will be part of the feeder reinforcement, the dc-link should provide significant cost advantage by delaying these outlays and saving the carrying charge for that capital. These benefits are determined by expanding (1) as follows:

$$\mathrm{NPV} = -CV_0 + \frac{FV_1}{(1+r)} + \frac{FV_2}{(1+r)^2} + \dots \frac{FV_t}{(1+r)^t} \quad (2)$$

Table V displays the expanded NPV calculation where CV_0 is the upfront cost of the dc-link (\$1.92 M), the future value benefits (FV_1, FV_2 and FV_3) are the savings from deferring the capital outlay of a new feeder (i.e., \$5.0M at a yearly carrying charge of 20% which is \$1.0 M) and the dc-link incremental losses. The positive NPV (\$0.531M) indicates the dc-link is more cost beneficial than the traditional solution.

For Case #2, (2) is also used but in this case, the savings are avoiding a network transformer build in Network #1 in year 0 (i.e., the dc-link is chosen over the traditional transformer replacement) and a transformer build in Network #2 in year 3. The NPV is once again positive indicating the dc-link is cost beneficial over the traditional solution.

In both cases, the dc-link's superior controls of active power and reactive power flow make it a more versatile solution in meeting not just peak load requirements but contingency and low load requirements as well. Table V displays some potential cost benefits using typical costs for feeder reinforcement and transformer replacement in a dense urban city.

The dc-link itself is assumed to require roughly the same maintenance as a transformer since they are both static devices. The dc-link is expected to be most useful in network designs where the cost of traditional solutions is also fairly expensive and complex (unlike radial or looped systems). Smaller networks will likely benefit more from a single dc-link but the technology and solution discussed in this paper is scalable and larger networks could have similar benefit from the build out of several dc-links. The dc-link technology itself is also fairly scalable and the size could be varied to the kW range or tens of MW range depending on network needs.

Additional benefits that may also accrue include crediting the dc-link with some portion of deferring an entire rebuild of a substation and/or some portion of the benefit of facilitating a CVO program.

VI. Conclusion

Utilizing a dc-link to gain both power flow and voltage regulation benefits in a dense urban network is a unique approach that provides a portfolio of benefits from a single piece of equipment. Power flow modeling has verified that the dc-link can be a useful tool in providing demand support from one network to the other as well as providing voltage support to both networks. In case study #1, usage of the dc-link was found to be an effective means of utilizing the excess feeder capacity on a feeder in network-3 to unload a feeder in network-1 and avoid feeder reinforcement costs as well as ultimately avoiding new feeder runs that would have to be placed under the river at great cost.

In case study #2, the dc-link was found to be a voltage support asset for both networks in both high load conditions (where it can supply reactive power) and low load condition (where it can absorb reactive power). Proper design of the dc-link as discussed in Fig. 6 can provide a means of utilizing both demand support between networks as well as voltage support for both networks in the same installation. This is an extremely valuable option over simply installing a network transformer or reinforcing/adding new feeders. Additional benefits that the dc-link may enable include deferred substation builds as well as enabling CVO in a network.

The dc-link is a promising technology expected to continue decreasing in price, gaining in efficiency and improving in performance because of the extensive growth in the power electronics market (particularly inverter based technologies that work with renewables like solar). If designed properly, the dc-links themselves can also become hubs for utilities to provide emergency generation, for customers to input their dc output generation (i.e., photovoltaics and wind) and/or for customers and utilities to tie in battery storage to reduce costs for themselves and to benefit the utility as well. Some type of creative rate making would be required to ensure both parties are incented to take these opportunities. These evolutions can occur over time and if implemented correctly will ultimately make the entire network a smarter grid.

References

[1] *Electrical Transmission and Distribution Reference Book*. East Pittsburgh, PA, USA: Westinghouse Electric Corp., 1964.

[2] Energy Information Agency Annual Energy Outlook (AEO) 2014 Early Release Overview, Apr. 14, 2014. [Online]. Available: http://www.eia.gov/

[3] 110th Congress United States of America, Title XIII, Energy Independence and Security Act of 2007.

[4] P. Chen, R. Salcedo, Q. Zhu, F. de León, D. Czarkowski, Z. P. Jiang, V. Spitsa, Z. Zabar, and R. Uosef, "Analysis of voltage profile problems due to the penetration of distributed generation in low-voltage secondary distribution networks," *IEEE Trans. Power Del.*, vol. 27, no. 4, pp. 2020–2028, Oct. 2012.

[5] J. John, "8 charts that illustrate progress on DOE's smart grid investment grants," Oct. 2003. [Online]. Available: http://www.greentechmedia.com

[6] V. Spitsa, X. Ran, R. Salcedo, J. Martinez, R. Uosef, F. de León, D. Czarkowski, and Z. Zabar, "On the transient behavior of large-scale distribution networks during automatic feeder reconfiguration," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 887–896, Jun. 2012.

[7] W. Kramer, S. Chakraborty, B. Kroposki, and H. Thomas, Advanced power electronic interfaces for distributed energy systems, Part 1: Systems and topologies, National Renewable Energy Laboratory, Golden, CO, USA, NREL/TP-581-42672 Tech. Rep., Mar. 2008.

[8] J. Bloemink and T. Green, "Benefits of distribution-level power electronics for supporting distributed generation growth," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 911–919, Apr. 2013.

[9] T. XiangQian, X. Keqing, S. Ming, and M. Xianhong, "Reactive power and unbalance compensation with DSTATCOM," in *Proc. 8th Int. Conf. Elect. Mach. Syst.*, Nanjing, China, Sep. 27–29, 2005, pp. 1181–1184.

[10] J. Guerrero, P. Loh, T. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and ac/dc microgrids," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1263–1270, Apr. 2013.

[11] J. Flottemesch and M. Rother, "Optimized energy exchange in primary distribution networks with dc links," in *Proc. IEEE Int. Conf. Utility Dereg., Restruct. Power Technol.*, Apr. 5–8, 2004, vol. 1, pp. 108–116.

[12] F. Belloni, R. Chiumeo, C. Gandolfi, and M. Brenna, "Application of back-to-back converters in closed-loop and meshed MV distribution grid," in *Proc. AEIT Annu. Conf.—From Research to Industry: The Need for a More Effective Technology*, Sep. 18–19, 2014, pp. 1–6.

[13] Northern Power Systems Flex Phase Power Converters. 2014. [Online]. Available: http://www.northernpower.com
[14] PR Newswire. Waitsfield, VT, USA, New York's Consolidated Edison awards contract to northern power for mobile power interface, Oct. 19, 2006. [Online]. Available: http://www.prnewswire.com
[15] C. Ashmore, "Transmit the light fantastic (HVDC power transmission)," *Power Engineer*, vol. 20, no. 2, pp. 24–27, Apr./May 2006.
[16] M. Behnke *et al.*, "Secondary network distribution systems background and issues related to the interconnection of distributed resources," National Renewable Energy Laboratory, Golden, CO, USA, Tech. rep. NREL/TP-560-38079, 2005.
[17] R. P. Fanning, "Implementation of networked primary and secondary distribution systems for U. S. utilities," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, 2003, vol. 4, pp. 2425–2429.
[18] Consolidated Edison,, "Part 105 filing concerning long island city electric service restoration," New York Public Service Commission Case 06-E-0894: Queens Power Outage, Sep. 25, 2006, pp. 1–185.
[19] *IEEE Standard Requirements for Secondary Network Protectors*, IEEE Standard C57.12.44, 2005.
[20] R. Salcedo, X. Ran, F. de León, D. Czarkowski, and V. Spitsa, "Long duration overvoltages due to current backfeeding in secondary networks," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2500–2508, Oct. 2013.
[21] V. Spitsa *et al.*, "Three-phase time-domain simulation of very large distributed networks," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 677–678, Apr. 2012.
[22] Z. Jiang and X. Yu, "Hybrid dc- and ac-linked microgrids: Towards integration of distributed energy resources," in *Proc. IEEE Energy 2030 Conf.*, 2008, pp. 1–8.
[23] M. Diaz-Aguilo, J. Sandraz, R. Macwan, F. de León, D. Czarkowski, C. Comack, and C. Wang, "Field-validated load model for the analysis of CVR in distribution secondary networks: Energy conservation," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2428–2436, Oct. 2013.

Damian Sciano (M'13), photograph and biography not available at the time of publication.

Ashar Raza, photograph and biography not available at the time of publication.

Reynaldo Salcedo (S'13), photograph and biography not available at the time of publication.

Marc Diaz-Aguilo, photograph and biography not available at the time of publication.

Resk Ebrahem Uosef (M'10), photograph and biography not available at the time of publication.

Dariusz Czarkowski (M'97), photograph and biography not available at the time of publication.

Francisco de León (S'98–M'92–SM'02–F'15), photograph and biography not available at the time of publication.