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Increasing Power Transfer Capacity of Distribution Networks Using Direct Current Feeders

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***Abstract*—**Economic and population growth in densely-populated urban areas introduce major challenges to distribution system operators, planers, and designers. To supply added loads, utilities are frequently forced to invest in new distribution feeders. However, this is becoming increasingly more challenging due to space limitations and rising installation costs in urban settings. This paper proposes the conversion of critical alternating current (ac) distribution feeders into direct current (dc) feeders to increase the power transfer capacity by a factor as high as four. Current trends suggest that the return of dc transmission, distribution, and utilization are inevitable. Since a total system-level transformation to dc operation is not possible in a short period of time due to the needed huge investments and utility unreadiness, this paper recommends that feeders that are expected to exceed their limits in near future are converted to dc. The increase in power transfer capacity is achieved through several key differences between ac and dc power transmission systems. First, it is shown that underground cables can be operated at higher dc voltage than the ac voltage for the same dielectric stress in the insulation. Second, cable sheath losses, due to induced voltages yielding circulation currents, that can be as high as phase conductor losses under ac operation, are not present under dc. Finally, skin and proximity effects in conductors and sheaths do not exist in dc cables. The paper demonstrates that in addition to the increased power transfer capacity utilities substituting ac feeders by dc feeders could benefit from significant lower costs and reduced losses. Installing dc feeders is less expensive than installing new ac feeders even when new trenches are not needed. Case studies using the IEEE 342-Node Low Voltage Networked Test System quantify the technical and economic benefits of dc feeders.

***Keywords*—**Dc power systems, distribution feeders, distribution networks, energy efficiency, power transfer capacity.

I. Introduction

With urban population and electrification growth, utilities are spending increasingly more money on expanding their infrastructure. Capital investments in distribution systems in the US have increased from $14 B/year in 1997 to $26 B/year in 2017. These investments are for installation and upgrade of underground cables, overhead lines, generators, transformers, circuit breakers, monitoring, relaying equipment, etc. [1]. A recent study focuses on the peak demand forecast for 2040 and 2060 in Los Angeles [2]. The paper concludes that the predicted peak demand increase would be as high as 30% and 45% by 2040 and 2060, respectively. Major factors contributing to these results are population growth and higher ambient temperatures due to climate change [2]. New York Independent System Operator (NYISO) also reports steady rise of the summer peak demand in New York City for 2017-2027. NYISO estimates that energy efficiency savings may result in 726 MW reduction of the summer peak demand in 2027 [3]. Con Edison of New York in its December 2010 report, looking ahead to 2030, presents two forecast scenarios for electricity demand in New York City. The baseline or "Plan" scenario assumes an annual growth rate of 0.8% between 2020 and 2030, based on a moderate growth rate in the City's economy. The second scenario assumes a higher growth rate of 1.7% per year from 2020 to 2030, based on a stronger New York City economy. These forecasts include the power saved by energy efficiency programs over the two decades [4].

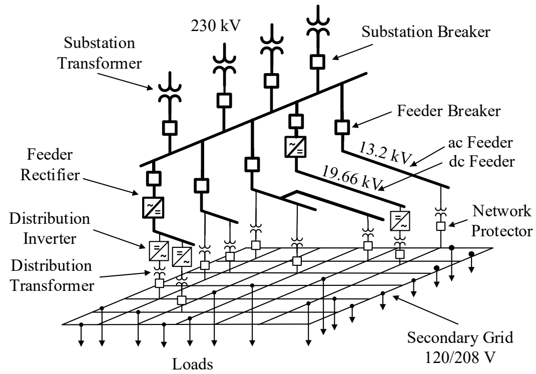

Fig. 1 Proposed dc distribution

Concurrently with demand grow, utilities are experiencing increasing levels of penetration of renewables and distributed generation (DGs). Although DGs may help flatten the peak demand, their application is limited due to overvoltage and overload problems leading to feeder and transformer congestions [5]-[11]. Moreover, DGs such as photovoltaics (PVs) and wind power greatly depend on the weather conditions. This fact is illustrated by the California Independent System Operator's (CAISO) infamous "duck curve" [12].

Electric vehicles (EVs) are one of the main drives of a renewable grid. They are environment-friendly and have a remarkable storage potential. However, they may also increase electricity demand of an average home by 25-30 % as reported by Duke Energy [13]. NREL estimated 38% rise in the US electricity demand by 2050 largely due to growing number of EVs [14]. Moreover, EVs may produce congestions (perhaps from uncontrolled charging during peak summer hours) in distribution feeders and substations [5]-[7], [15]-[17]. EV charging will increase demand, potentially magnifying the

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existing peak load or creating new peaks [18].

It is clear that there is a steady growth of electricity peak demand in urban areas. To address this trend our paper proposes to transform critical ac distribution feeders into dc feeders to increase the power transfer capacity. Initially, and as the progressive conversion to dc is realized, a hybrid ac/dc system as illustrated in Fig. 1 is foreseen. System-wide conversion from ac to dc operation requires gigantic investments and may not be feasible at this moment or in the near future. Hence, to our best knowledge, this paper introduces for the first time a gradual transition where only existing primary feeders that currently exceed (or are expected to exceed soon) their power flow limits are upgraded to dc. As shown numerically in this paper, conversion to dc operation results in considerably lower costs when compared with re-conducting an ac feeder and much more so when excavating trenches is needed. This is due to the high costs of installations in urban distribution networks, while power electronics equipment costs are reducing and efficiency is rising.

Electricity distribution in metropolitan systems is mainly underground. For instance, currently, 86% of electric load and 82% of customers in New York City are served by underground distribution networks [19]. Therefore, this paper focuses on upgrading the capacity of underground cables.

Besides the cost efficiency of dc feeders, they also provide increased power transfer capacity achieved through key differences between ac and dc configurations:

1) the possibility to operate dc feeders at higher voltage.
2) dc transmission does not cause losses due to sheath circulating currents in multiple-point bonded cables.
3) dc transmission does not have losses due to skin and proximity effects (in conductors and sheaths).

A numerical example based on the IEEE 342-Node Low Voltage Network Test System [20] shows that the power transfer capacity can be increased by 3.92 times without any additional underground power cable or line installation when dc is used instead of ac.

The main contribution of this paper is to provide a better alternative to increase power transfer capacity of existing distribution feeders than installing new ac cables. The use of dc feeders avoids or defers investments that otherwise would be necessary to increase the power transfer capacity of the constantly growing physically-constrained distribution networks. This is vital because space and regulation issues in large cities not only require huge capital investments, but also significantly lengthen the time frame to complete an installation (disrupting the life of neighboring business and inhabitants for a period of time).

II. Proposed DC Distribution

The proposed dc distribution is illustrated in Fig. 1. The system utilizes the existing ac distribution network and requires only feeder rectifiers and distribution inverters as depicted in the figure. Since not all feeders may be congested, dc conversion is applied only to those where power transfer capacity upgrade is needed the most. The voltage is rectified at the head of a congested feeder and power is delivered in dc form to distribution inverters. Then, after the inversion takes place the existing step-down distribution transformers pick up the power and electricity is delivered to the customers as it would normally be done in today's ac system. As the demand for feeder upgrading increases, utilities can utilize more dc feeders which may bring up eventually the need to have dc bars at the substation level as in ac/dc hybrid systems.

Besides power transfer upgrades, dc distribution may also help reduce fault current magnitudes since it serves as a dc-link between the substation and secondary network. The dc-link interrupts the fault in less than a quarter of a cycle and keeps the fault current to below 2 per unit during this time period. This is significantly better than conventional breakers or switches which require a minimum of 3 to 5 cycles to interrupt a fault fed by ac lines that might reach 7 to 10 per unit [21].

Current and future developments in power electronics converters are the deciding factor in the implementation of the proposed dc distribution feeders. The efficiency of substation rectifiers and distribution inverters is vital in promoting dc distribution. Diode-based and voltage-source converter (VSC) HVDC-rectifier stations used for the connection of offshore wind farms to the grid can be operated with efficiencies as high as 99.5% [22]. Furthermore, paralleling dc-dc converters as described in [23] allows achieving the maximum efficiency even when the converters are at 10% loading [24]. MW sized dc-dc converters are already in use in offshore wind farms. A demonstration of a 5 MW medium-voltage dc-dc converter has been commissioned at the E.ON Energy Research Center of the RWTH Aachen University [25]. Modular Multilevel Converters (MMCs) are the state of the art in converter technology and an extremely attractive alternative to VSC. MMCs with a scalable technology can reach any operating voltage from the medium (2.3 kV to 13.8 kV) to high-voltage (33 kV to 400 kV) and power rating of 226 kW to1000 MW [26]. Efficiency and design improvements of MMCs are one of the hot topics today in power electronics research. High-power MMCs with SiC JFETs may provide efficiency as high as 99.8% [27].

Although dc distribution systems face many challenges such as: the lack of regulation and standardization, the need for development of dc protection devices, and schemes that ensure safe and reliable operation, recent advances in dc technology show that utilizing dc in distribution networks is not far off. Several organizations such as Emerge Alliance (EA), the European Telecommunications Standards Institute (ETSI), the International Electrotechnical Commission (IEC), IEEE and others, are already actively developing the necessary regulation and standards. Dc circuit breakers are already available rated up to 150 kA/750 V from ABB, Schneider Electric, and others. Superconducting fault current limiters can be used to reduce dc fault current and help a dc circuit breaker interrupt the fault current.

III. Ac vs. Dc

This section first analyzes the differences between ac and dc for distribution systems. Then, it derives the potential power transfer capacity upgrade of existing ac feeders when converted to dc.

A. DC Operating Voltage

Arrillaga [28] based on the electric field strength proposes that an ac underground cable can be operated at a dc voltage as high as 2.94 times the phase-to-ground ac rms voltage. However, the statement does not take into account the material properties used in cables. Nowadays, ac cable insulation is mainly made of polymeric materials such as XPLE and EPR, which have superior properties over paper insulation.

The electric field distribution in ac cables is determined by the geometry of the insulation and relative permittivity that are not affected by local electric fields and temperature. On the other hand, the electric field distribution in dc cables also depends on the material conductivity, which depends on operating temperature. Hence as the temperature close to the conductor increases, a phenomenon called electric field inversion may occur where the highest electric stress is observed at the outer portion of the insulation [29], [30].

Accumulation of space charges in the insulation bulk under dc voltage has to be considered. Space charge build-up may significantly reduce the breakdown voltage of the insulation, especially in the interfaces between the semiconducting layer and main insulation. Three insulation and two semiconducting types were tested using the Pulsed Electro Acoustic (PEA) technique for space charge accumulation in [29]. Different combinations of the semiconducting and insulation materials yield different threshold field, 10 kV/mm and 12 kV/mm, and 4 kV/mm and 5 kV/mm at 25 °C and 70°C, respectively. Space charge measurements using PEA reported in [30] show that XLPE cables have a threshold applied field of 8 kV/mm and 3 kV/mm at 25 °C and 70 °C, respectively. When the applied voltage is below the threshold, the amount of injected charge is low and the insulation behaves according to Ohm's Law. This ensures that there is no net charge trapped in the insulation bulk. Hence, to establish a safe dc operating voltage utilities need to test their cables for space charge accumulation. This will give confidence that the existing cables will not degrade and experience when operated under dc voltage.

There are four major distribution (ac) voltage insulation classes for distribution cables in North America: 5 kV, 15 kV, 25 kV, and 35 kV. The 15 kV voltage class is the most widespread and serves 62.4% of the total load [31]. The IEEE 342-node low voltage networked test system [20] has primary feeders operating at 13.2 kV and utilizes 15 kV cables. These cables are manufactured at 100% and 133% insulation levels that correspond to main insulation thickness of 4.445 mm (175 mils) and 5.588 mm (220 mils), respectively. For a two-wire dc system with mid-point grounded [32] (see Fig. 2) and assuming 3 kV/mm applied field threshold one can safely achieve dc voltages of 13.335 kV and 16.764 kV for 100% and 133% insulation levels for 15 kV ac cables.

B. Sheath/Shield Losses in Primary Feeders

For the most part in North America, the metallic sheath (or shield) of distribution class cables is normally multipoint solidly grounded. The initial installation cost and additional maintenance associated with cross-bonded sheath makes this option less economically attractive for distribution class feeders [33]. However, sheath losses resulting from multipoint solidly grounded sheaths may be as high as (or even exceed) conductor losses depending on the separation distance between the cables and sheath resistance. A numerical example in the next section demonstrates this fact. Since dc does not induce voltage, one can eliminate entirely the sheath losses, while making no changes to the existing multi-point bonding.

The sheath loss factors for single-circuit lines with sheaths bonded at both ends of electrical sections in trefoil and flat formations were introduced by Arnold [34] and appear in the IEC Standard [35] as well. For the sheath loss factors in double-circuit lines the modified Carson's equations [36] are used.

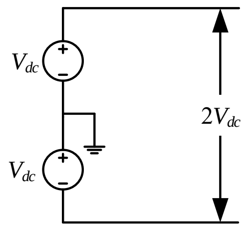

Fig. 2 Two-wire dc system with mid-point grounded [32]

C. Skin and Proximity Effects

Dc distribution is also immune to skin and proximity effects. For comparison, skin and proximity effects in ac distribution are computed according to [35]. Skin effect can account for up to 23.3% (for copper) and 10% (for aluminum) of the dc resistance depending on conductor size. Combined skin and proximity effect for multi-conductor cables or cables in ducts can be as high as 82% and 56% for 2000 kcmil copper and aluminum conductors, respectively [37].

D. Power Transfer Calculations

Primary feeders are usually installed in multiple parallel circuits, two or more, for increased reliability and service quality. To illustrate the power transfer calculations double circuit primary feeders are assumed in this paper. Thermal limits of feeders have to be met, i.e. cable losses are kept equal for both cases. For simplicity power losses are considered on per cable basis. Thus ac and dc power losses in one cable are given by Joule's Law: $P_{ac}^{loss} = R_{ac} I_{ac}^2$ and $P_{dc}^{loss} = R_{dc} I_{dc}^2$ where, R_{ac} is the cable positive-sequence resistance including skin and proximity effect, and sheath losses; R_{dc} is the cable dc resistance; I_{ac} is the ac rms current; and I_{dc} is the dc current. Then dc current in terms of ac rms current for the same losses is given by:

$$I_{dc} = I_{ac}\sqrt{\frac{R_{ac}}{R_{dc}}} \quad (1)$$

The ac resistance in terms of the dc resistance taking into account skin and proximity effects, and sheath loss factors yields [35]:

$$R_{ac} = R_{dc}(1 + y_s + y_p)(1 + \lambda) \tag{2}$$

Thus, (1) becomes:

$$I_{dc} = I_{ac}\sqrt{(1 + y_s + y_p)(1 + \lambda)} \tag{3}$$

where, y_s:skin effect factor; y_p: proximity effect factor; λ: sheath loss factor.

Active power delivered by a double-circuit ac feeder is given by:

$$P_{ac} = 2 \times (3V_{ac}I_{ac}\cos\varphi) = 6\,V_{ac}I_{ac}\cos\varphi \tag{4}$$

Since there are six wires in a double-circuit line one may have three parallel two-wire dc systems with mid-point grounding (see Fig. 2). Then total power in this dc feeder is:

$$P_{dc} = 3 \cdot 2V_{dc}I_{dc} = 6V_{dc}I_{ac}\sqrt{(1 + y_s + y_p)(1 + \lambda)} \tag{5}$$

A power transfer increase factor can be defined as:

$$\kappa_{double} = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc}}{V_{ac}}\frac{\sqrt{(1+y_s+y_p)(1+\lambda)}}{\cos\varphi} \tag{6}$$

If there is only one single-circuit three phase line available, the power transfer increase factor is reduced by one third since a cable is not used:

$$\kappa_{single} = \frac{P_{dc}}{P_{ac}} = \frac{2}{3}\frac{V_{dc}}{V_{ac}}\frac{\sqrt{(1+y_s+y_p)(1+\lambda)}}{\cos\varphi} \tag{7}$$

As it will be shown in the next section, these factors can be as high as 3.92 and 2.49, respectively.

E. Power Electronics and Feeder Losses

As it was mentioned earlier, only the feeders that are expected to exceed their power flow limits, are recommended for conversion to dc. Hence, power electronics equipment is required to be installed at the beginning and end of the dc feeder. Thus, the total losses including conversion losses in a dc feeder consisting of 6 cables (obtained from a double-circuit three phase ac feeder) are:

$$PL_{dc} = 6R_{dc}I_{dc}^2 + P_{dc}\cdot(1 - 0.998^2) = \frac{R_{dc}}{6}\left(\frac{P_{dc}}{V_{dc}}\right)^2 + 0.004P_{dc} \tag{8}$$

On the other hand double-circuit ac feeder power losses are:

$$PL_{ac} = 6R_{ac}I_{ac}^2 = \frac{R_{ac}}{6}\left(\frac{P_{ac}}{V_{ac}\cos\varphi}\right)^2 \tag{9}$$

For the same active power delivered to the receiving end of the line we get (after some algebra) the following expression:

$$\frac{PL_{ac}}{PL_{dc}} = \frac{\frac{R_{ac}}{6}\left(\frac{P_{ac}}{V_{ac}\cos\varphi}\right)^2}{\frac{R_{dc}}{6}\left(\frac{P_{dc}}{V_{dc}}\right)^2 + 0.004P_{dc}} = \frac{(1+y_s+y_p)(1+\lambda)}{\left(\frac{V_{ac}\cos\varphi}{V_{dc}}\right)^2 + \frac{0.004V_{ac}\cos\varphi}{R_{dc}I_{ac}}} \tag{10}$$

A numerical example in the next section demonstrates that the ratio of ac losses to dc losses is greater than 1 suggesting that the conversion losses are compensated by the lower dc resistance, making dc more favorable than ac on this front as well. Similarly, one may obtain ac to dc feeder loss ratio when single-circuit line is transformed to a single dc line as:

$$\frac{PL_{ac}}{PL_{dc}} = \frac{\frac{R_{ac}}{3}\left(\frac{P_{ac}}{V_{ac}\cos\varphi}\right)^2}{\frac{R_{dc}}{2}\left(\frac{P_{dc}}{V_{dc}}\right)^2 + 0.004P_{dc}} = \frac{2}{3}\frac{(1+y_s+y_p)(1+\lambda)}{\left(\frac{V_{ac}\cos\varphi}{V_{dc}}\right)^2 + \frac{0.008V_{ac}\cos\varphi}{3R_{dc}I_{ac}}} \tag{11}$$

F. Cost of Feeder Losses

This section shows that ac feeder losses are greater than dc feeder losses. Annual equivalent energy cost due feeder losses can be defined as follows [38]:

$$AEC = 3R_{ac}I_{ac}^2 \cdot EC \cdot F_{LL} \cdot F_{LS} \cdot F_{LSA} \cdot 8760\ [\$/\text{mi}] \tag{12}$$

EC: cost of energy [$/kWh]; F_{LL}: load-location factor, $= s/L$;F_{LS}: loss factor; F_{LSA}: loss-allowance factor; s: distance of point on feeder where total feeder load can be assumed to be concentrated for the purpose of calculating feeder losses [mi]; L: total feeder length [mi].

The loss factor represents the ratio of the average annual power loss to the peak annual power loss and may be computed for urban areas using

$$F_{LS} = 0.3F_{LD} + 0.7F_{LD}^2 \tag{13}$$

F_{LD}: load factor (ratio of average load to peak load over a specified period of time, a year in this case).

The loss-allowance factor covers the effect of the additional losses in the power system due to power transmission from the generating units to the distribution substation. In [38] this factor is taken as 1.03 but in our calculation we assume it as 1. Moreover, we consider F_{LL} = 1 as total feeder load is the same along the feeders of interest.

IV. IEEE 342 Node Low Voltage Network Test System

The IEEE 342-node low voltage networked test system is representative of a low voltage network as deployed in urban areas in North America [20]. The system is supplied from a 230 kV substation containing two 50 MVA 230/13.2 kV step-down transformers supplying eight radial 13.2 kV primary feeders. These eight primary feeders are 2500 ft. long and supply a 120/208 V secondary network and eight 277/480 V spot networks via 68 delta/grounded-wye transformers. The total load on the system is approximately 50 MVA.

The one-line diagram of primary distribution feeders (see Fig. 2 of [20]) reveals that feeders 2-3, feeders 4-5 and feeders 6-7 can be combined to form three dc circuits (see Fig. 3) as they run in parallel, start and end in very close locations. OpenDSS power flow simulation results for the above-mentioned eight primary feeders are given in Table I.

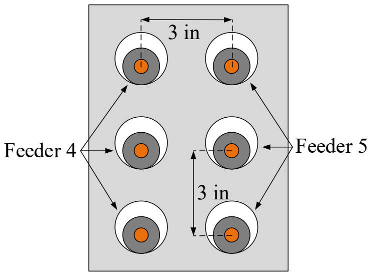

Fig. 3 Double-circuit three phase ac feeder in an underground duct bank

TABLE I
OPENDSS POWER FLOW SIMULATION RESULTS

Feeder #	1	2	3	4
Positive sequence current [A]	268	243	270	246
Feeder #	5	6	7	8
Positive sequence current [A]	270	285	232	251

A. Power Transfer Increase Factor

The primary feeder conductor data and spacing are presented in Tables I and II. Skin and proximity effect factors have been found as 1.2% and 2.1% according to the IEC Standard 60287-1-1 [35]. For the installation shown in Fig. 3 the sheath loss factor is 87% whereas for single-circuit line the sheath loss factor is 69%.

Kersting [39] provides more details on the IEEE distribution test feeders and for the primary feeder cable the diameter over insulation is 1.64 in which makes the insulation thickness 0.258 in. Assuming 3 kV/mm (conservative value) applied field threshold for space charge accumulation we can safely operate the cable at dc voltage of 19.66 kV. Then using power factor equal to 0.9, the dc power transfer increase factor is computed as:

$$\kappa_{double} = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc}}{V_{ac}} \frac{\sqrt{(1+y_s+y_p)(1+\lambda)}}{\cos\varphi} = 3.92$$

Feeders 1 and 8 can also be transformed to dc feeders with power transfer increase factor of:

$$\kappa_{single} = \frac{P_{dc}}{P_{ac}} = \frac{2V_{dc}}{3V_{ac}} \frac{\sqrt{(1+y_s+y_p)(1+\lambda)}}{\cos\varphi} = 2.49$$

As the above result shows, one can substantially increase the power transfer of primary feeders by substituting ac feeders with dc feeders. dc distribution utilizes the existing underground lines and requires no construction of additional lines. The only investments needed are power electronics devices.

V. TECHNICAL AND ECONOMIC BENEFITS OF DC FEEDERS

New York City summer peak demand is forecasted to reach 16,780 MW by 2030 considering strong economy and energy efficiency programs [40]. Summer peak for 2018 was recorded as 12,635 MW on August 29th [41]. Then, the expected total peak demand growth by 2030 is about 33%. Total load on the IEEE 342 node test system is approximately 50 MVA. Thus by 2030 the peak demand is increased by 16.5 MVA and becomes 66.5 MVA. It is assumed that the peak demand growth is not uniform across the system but rather concentrated in several spot networks, namely spot networks 3, 4 and 7. OpenDSS power flow simulations give the feeder currents printed in Table II. Although the feeder currents are well under the line capacity of 615 A, utilities that operate highly meshed distribution systems as the IEEE 342 node test system frequently use the N-2 reliability criterion. This ensures that the peak demand is met without stressing network components beyond design limits when any two network feeders are out of service. We also analyze N-1 contingency scenarios where one feeder is out of service; calculations are shown in Table III for best and worst cases, respectively. For the N-2 contingency with two feeders out of service yields the results provided in Table IV again for best and worst scenarios. Clearly under double contingency the IEEE 342 node test system is unable to meet the design criteria and requires power transfer capacity upgrade on its primary feeders 1, 4, 5 and 8.

TABLE II
OPENDSS POWER FLOW SIMULATION RESULTS FOR 2030 PEAK DEMAND

Feeder #	1	2	3	4
Positive sequence current [A]	388	261	291	506
Feeder #	5	6	7	8
Positive sequence current [A]	406	304	249	509

TABLE III
N-1 CONTINGENCY SIMULATION RESULTS FOR 2030 PEAK DEMAND (BEST / WORST)

Feeder #	1	2	3	4
Positive sequence current [A]	401/524	252/332	281/370	498/668
Feeder #	5	6	7	8
Positive sequence current [A]	407/547	277/377	245/324	511/672

TABLE IV
N-2 CONTINGENCY SIMULATION RESULTS FOR 2030 PEAK DEMAND (BEST / WORST)

Feeder #	1	2	3	4
Positive sequence current [A]	420/660	247/455	259/503	506/868
Feeder #	5	6	7	8
Positive sequence current [A]	436/709	273/504	253/432	519/895

TABLE V
NEW FEEDER INSTALLATION COSTS IN NEW YORK CITY

	Unit count	Units	Cost
Primary Cable 250' Section	Sections	1	$38,903
Roadway Primary Excavation	Feet	1	$580
Underground Manhole Vault	Per structure	1	$123,865

A. Cost of Power Transfer Capacity Upgrade by Installing New Feeders

Construction of underground feeders results in massive costs. Metropolitan areas pose a wide variety of underground obstacles, such as existing utilities, natural features, topography, major roadways, or underpasses. Table V presents new feeder installation cost per unit length in New York City [42].

Primary feeders 1, 4, 5 and 8 are 2500 ft. long, equivalent to 40 sections of 250 ft. (total length of 10,000 ft.) and total cost of possible re-conducting the cables would be $1,556,120 assuming the existing ducts have enough space to fit larger cables. Otherwise, installation of the new feeders would bring up excavation costs that for four feeders would be $4,350,000 (feeders 4-5 are considered in the same duct banks resulting in 7,500 ft. of excavation). Here underground manhole vault and duct bank costs are not included. Similar numbers can be obtained using the data reported by the US Department of Energy in [43]. Average cost per mile of underground distribution feeder in urban areas is $2,820,650. Then the cost of upgrading of the above-mentioned feeders is $5,342,139.

B. Cost of Power Transfer Capacity Upgrade by Converting to dc Feeders

As the power electronics and especially high power and high voltage converter technology continuously evolve, their cost constantly decreases. Cost of MMCs depends on the power density and voltage level. Tu [44] provides the cost of a medium-voltage 3 MW MMC to be around $70,000 (see Fig. 1 (a) of [44]). Then for 4 feeders we need 6 MMCs (again feeders 4-5 are considered in the same duct banks) which will cost $420,000. This is a much lower cost than installing new cables that would have cost $1,556,120. Furthermore, this approach requires minimal time for power transfer capacity upgrade and presents no inconvenience to the traffic and public.

Dc feeder currents obtained from OpenDSS power flow simulations are shown in Table VI. Since OpenDSS solves for a single frequency and cannot explicitly be applied to dc systems we devised a workaround to represent dc feeders in our simulations:

1) Reactance of the dc feeders are set to zero
2) Ensure no reactive power flow in the feeders by placing capacitors at the receiving end
3) MMCs are realized using transformers to obtain dc operating voltage in the respective feeders

TABLE VI
OPENDSS POWER FLOW SIMULATION RESULTS FOR 2030 PEAK DEMAND USING DC FEEDERS

Feeder #	1 (dc)	2	3	4 (dc)	4-5 (dc)
Positive sequence current [A]	185	264	290	145	145
Feeder #	5 (dc)	6	7	8 (dc)	
Positive sequence current [A]	145	309	251	250	

TABLE VII
N-1 CONTINGENCY SIMULATION RESULTS FOR 2030 PEAK DEMAND USING DC FEEDERS

Feeder #	1 (dc)	2	3	4 (dc)	4-5 (dc)
Positive sequence current [A]	198/300	270/337	324/363	65/202	65/202
Feeder #	5 (dc)	6	7	8 (dc)	
Positive sequence current [A]	65/202	330/382	258/319	259/496	

TABLE VIII
N-2 CONTINGENCY SIMULATION RESULTS FOR 2030 PEAK DEMAND USING DC FEEDERS

Feeder #	1 (dc)	2	3	4 (dc)	4-5 (dc)
Positive sequence current [A]	216/423	288/449	337/496	61/245	61/245
Feeder #	5 (dc)	6	7	8 (dc)	
Positive sequence current [A]	61/245	365/512	285/438	277/652	

N-1 and N-2 contingency simulations' results are provided in Tables VII and VIII. Note that the obtained feeder currents are well below the dc ampacity of 800 A computed using (3). It is worth mentioning that feeders 1 and 8 under dc operation use only two conductors while feeders 4 and 5 form three dc feeders which increase the reliability of the network. All these make dc feeders unequivocally a superior alternative to ac feeders.

C. Ac vs. Dc Feeder Losses and their Cost

Losses in feeders 1, 4, 5 and 8 under ac are computed using currents in Table II while under dc operation currents from Table VI are used. New York City electricity consumption in 2030 is expected to be about 52 TWh [45], then F_{LD} = 0.354. Average electricity price in New York City is 21 cents per kWh [46].

Feeder 1:

$$I_{ac} = 388 \text{ A}$$

$$\frac{FL_{ac}}{FL_{dc}} = \frac{2}{3}\frac{(1+y_s+y_p)(1+\lambda)}{\left(\frac{V_{ac}\cos\varphi}{V_{dc}}\right)^2+\frac{0.008V_{ac}\cos\varphi}{3R_{dc}I_{ac}}} = 1.20$$

AEC_{ac} = $80,709 and AEC_{dc} = $67,179, which means $13,530 can be saved annually.

Feeders 4 and 5:

$$I_{ac} = \frac{506+406}{2} = 456 \text{ A}$$

$$\frac{FL_{ac}}{FL_{dc}} = \frac{(1+y_s+y_p)(1+\lambda)}{\left(\frac{V_{ac}\cos\varphi}{V_{dc}}\right)^2+\frac{0.004V_{ac}\cos\varphi}{R_{dc}I_{ac}}} = 1.61$$

AEC_{ac} = $246,700 and AEC_{dc} = $153,614 giving $93,086 of savings annually.

Feeder 8:

$$I_{ac} = 509 \text{ A}$$

$$\frac{FL_{ac}}{FL_{dc}} = \frac{2}{3}\frac{(1+y_s+y_p)(1+\lambda)}{\left(\frac{V_{ac}\cos\varphi}{V_{dc}}\right)^2+\frac{0.008V_{ac}\cos\varphi}{3R_{dc}I_{ac}}} = 1.52$$

AEC_{ac} = $138,896 and AEC_{dc} = $91,578, achieving $47,318 in savings per year.

VI. CONCLUSION

Population and economic growth together with rising levels of penetration of EVs and DGs are becoming the main focus of metropolitan distribution networks. Due to space and regulation constraints, utilities probably will have difficulties supplying electricity to the increasing number of loads producing line congestions. This paper proposes converting some existing ac feeders to dc in densely-populated urban areas to increase power transfer capacity without any additional construction. A numerical example using the IEEE 342-node low voltage networked test system indicates that power transfer capacity of dc feeders can be as high as 3.92 times that of ac feeders. Additionally, converting an ac feeder into a dc feeder requires minimal time and no interference with daily life of the neighboring businesses and residents. In addition, dc feeders offer significantly lower costs when compared to installing new ac feeders at reduced feeder losses. As dc systems become more attractive than ac systems this paper has proposed a feasible and economically superior strategy for increasing the power transfer capacity of present ac distribution systems by converting them to dc operation.

References

[1] Major utilities continue to increase spending on U.S. electric distribution systems, US Energy Information Administration, Jul. 2018, https://www. eia.gov/todayinenergy/detail.php?id=36675 (Accessed: Aug. 29, 2019).

[2] D. Burillo, M. V. Chester, S. Pincetl, E. D. Fournier, and J. Reyna, “Forecasting peak electricity demand for Los Angeles considering higher air temperatures due to climate change,” Appl. Energy, vol. 236, pp. 1–9, Feb. 2019.

[3] New York Independent System Operator (2017), “2017 Load & Capacity Data, Gold Book.”

[4] Consolidated Edison Company of New York, Inc. (2011), “Electric Long-Range Forecast.”

[5] S. Huang, Q. Wu, S. S. Oren, R. Li, and Z. Liu, “Distribution locational marginal pricing through quadratic programming for congestion management in distribution networks,” IEEE Trans. Power Syst., vol. 30, no. 4, pp. 2170-2178, July 2015.

[6] S. Huang, Q. Wu, L. Cheng, and Z. Liu, “Optimal reconfiguration-based dynamic tariff for congestion management and line loss reduction in distribution networks,” IEEE Trans. Smart Grid, vol. 7, no. 3, pp. 1295-1303, May 2016.

[7] S. Huang, Q. Wu, L. Cheng, Z. Liu, and H. Zhao, "Uncertainty management of dynamic tariff method for congestion management in distribution networks," IEEE Trans Power Syst., vol. 31, no. 6, pp. 4340-4347, Nov. 2016.

[8] F. Demailly, O. Ninet, and A. Even, "Numerical tools and models for Monte Carlo studies of the influence on embedded generation on voltage limits in LV grids," IEEE Trans. Power Delivery, vol. 20, no. 3, pp. 2343-2350, July 2005.

[9] A. Elmitwally, M. Elsaid, M. Elgamal, and Z. Chen, “A fuzzy-multiagent self-healing scheme for a distribution system with distributed generations,” IEEE Trans. Power Syst., vol. 30, no. 5, pp. 2612-2622, Sept. 2015.

[10] T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Smart decentralized control of dg for voltage and thermal constraint management," IEEE Trans Power Syst., vol. 27, no. 3, pp. 1637-1645, Aug. 2012.

[11] 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, October 2012, pp. 2020-2028.

[12] California Independent System Operator (2016), “What the duck curve tells us about managing a green grid”, Folsom, CA. (Online). Available: https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_ FastFacts.pdf (Accessed: Aug. 29, 2019).

[13] Sustainable Brands, “Could EVs Be the Secret to a 100% Renewable Grid?,” (Online). Available: https://sustainablebrands.com/read/cleantech /could-evs-be-the-secret-to-a00-renewable-grid (Accessed: Aug. 29, 2019).

[14] NREL, “Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States,” Jun. 2018.

[15] K. C. Nyns, E. Haesen, and J. Driesen, “The impact of charging plug-in hybrid electric vehicle on a residential distribution grid,” IEEE Trans. Power Syst., vol. 25, no. 1, pp. 371–380, Feb. 2010.

[16] R. C. Leou, C. L. Su, and C. N. Lu, "Stochastic analyses of electric vehicle charging impacts on distribution network," IEEE Trans. Power Syst., vol. 29, no. 3, pp. 1055-1063, May 2014.

[17] B. P. Bhattarai, M. Lévesque, M. Maier, B. Bak-Jensen, and J. Radhakrishna Pillai, "Optimizing electric vehicle coordination over a heterogeneous mesh network in a scaled-down smart grid testbed," IEEE Trans. Smart Grid, vol. 6, no. 2, pp. 784-794, March 2015.

[18] L. Kelly, A. Rowe, and P. Wild, “Analyzing the impacts of plug-in electric vehicles on distribution networks in British Columbia,” Proc. IEEE Electrical Power and Energy Conf., 2009, pp. 1–6.

[19] City of New York (2013), “A Stronger, More Resilient New York.”

[20] K. Schneider, P. Phanivong, and J. S. Lacroix, “IEEE 342-node low voltage networked test system,” 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014, pp. 1-5.

[21] D. Sciano, A. Raza, R. Salcedo, M. Diaz-Aguilo, R. E. Uosef, D. Czarkowski, and F. de León, “Evaluation of dc-links on dense-load urban distribution networks”, IEEE Trans. Power Del., Vol. 31, No. 3, June 2016, pp. 1317-1326.

[22] S. Bernal-Perez, S. Ano-Villalba, R. Blasco-Gimenez, and J. Rodriguez-D'Derlee, "Efficiency and fault ride-through performance of a diode-rectifier- and VSC-inverter-based HVDC link for offshore wind farms," IEEE Trans. Ind. Electron., vol. 60, no. 6, pp. 2401-2409, June 2013.

[23] D. J. Hammerstrom, “ac versus dc distribution systems – Did we get it right?,” 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, 2007, pp. 1-5.

[24] General Motors Corporation, “High efficiency power system with plural parallel DC/DC converters,” US Patent 6 166 934, Jun. 30, 1999.

[25] N. Soltau, H. Stagge, R. W. De Doncker, and O. Apeldoorn, “Development and demonstration of a medium-voltage high-power DC-DC converter for DC distribution systems,” 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Galway, 2014, pp. 1-8.

[26] S. Du, A. Dekka, B. Wu, and N. Zargari, Modular Multilevel Converters: Analysis, Control, and Applications. Hoboken, NJ: Wiley-IEEE Press, 2018.

[27] D. Peftitsis et al., "High-Power Modular Multilevel Converters With SiC JFETs," in IEEE Trans. Power Electronics, vol. 27, no. 1, pp. 28-36, Jan. 2012.

[28] J. Arrillaga, High Voltage Direct Current Transmission, IET Power and energy series 29, 2008.

[29] D. Fabiani et al., "Polymeric HVDC Cable Design and Space Charge Accumulation. Part 1: Insulation/Semicon Interface," in IEEE Electrical Insulation Magazine, vol. 23, no. 6, pp. 11-19, Nov.-Dec. 2007.

[30] S. Delpino et al., "Feature article - Polymeric HVDC cable design and space charge accumulation. Part 2: insulation interfaces," in IEEE Electrical Insulation Magazine, vol. 24, no. 1, pp. 14-24, Jan.-Feb. 2008.

[31] W. M. Strang et al., "Distribution line protection practices industry survey results," in IEEE Trans. Power Delivery, vol. 10, no. 1, pp. 176-186, Jan. 1995.

[32] V. K. Mehta and R. Mehta, Principles of Power System, S. Chand and Company Ltd., New Delhi, 2001.

[33] IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV, IEEE Standard 575-2014, 2014.

[34] A. H. M. Arnold, “The theory of sheath losses in single-conductor lead-covered cables,” Jour. IEE, vol. 67, no. 384, pp. 69-89, 1928.

[35] Electric cables—Calculation of the current rating—Part 1–1: Current rating equations (100% load factor) and calculation of losses. General, IEC Standard 60287-1-1 (2001-11).

[36] W. H. Kersting, Distribution System Modeling and Analysis. Boca Raton, FL: CRC, 2002.

[37] D. G. Fink and H. W. Beaty, Standard Handbook for Electrical Engineers, 16th Ed., McGraw-Hill, New York, 2013.

[38] T. Gonen, Electric Power Distribution Engineering. Boca Raton, FL: CRC, 2014.

[39] W. H. Kersting, “Radial distribution test feeders,” 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194), Columbus, OH, USA, 2001, pp. 908-912 vol.2.

[40] Energy Committee of the New York Building Congress, “Powering New York City through 2030,” Oct. 2011.

[41] Consolidated Edison Company of New York, Inc., “Con Edison Customers Set Peak Usage Record for 2018”. (Online). Available: https://www.coned.com/en/about-con-edison/media/news/20180829/con-edison-customers-set-peak-usage-record-for-2018. (Accessed: Aug. 29,

2019).
[42] Personal communications with Consolidated Edison Company of New York distribution engineers.
[43] The U.S. Department of Energy, "Quadrennial Technology Review 2015, Chapter 3: Enabling Modernization of the Electric Power System," (Online). Available: https://www.energy.gov/sites/prod/files/2015/09/f26 /QTR2015-3F-Transmission-and-Distribution_1.pdf (Accessed: Aug. 29, 2019).
[44] P. Tu, S. Yang, and P. Wang, "Reliability- and cost-based redundancy design for modular multilevel converter," in IEEE Trans. Industrial Electronics, vol. 66, no. 3, pp. 2333-2342, March 2019.
[45] NYISO, 2019 Load and Capacity Data, Apr. 2019.
[46] U.S. Bureau of Labor Statistics, "Average Energy Prices, New York-Newark-Jersey City – May 2018. (Online). Available: https://www.bls.go v/regions/new-york-new-jersey/news-release/2018/averageenerprices_ne wyorkarea_20180613.htm (Accessed: Aug. 29, 2019).