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Transition from alternating current to direct current low voltage distribution networks

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Abstract: Maximising the capacity of the existing alternating current (AC) distribution network infrastructure by conversion to direct current (DC) may hold significant advantages. In particular it may provide a greater flow of electrical energy within urban areas, allowing a lower investment cost for adoption of electrical vehicles and domestic heating. Integration with Smart Grid applications will require maintained levels of reliability, and improved efficiency and flexibility. The transition of the cable infrastructure from the legacy low voltage AC system to low voltage DC is considered in this study. In particular this study investigates the limitations of DC supplied through the existing distribution network without major re-construction, and proposes optimal configurations that could be adopted in a smart-DC distribution network. The implications for power flow in the network are considered with regards to existing cable limitations. It is concluded that a better understanding of cable and joint reliability is required before such changes are made to existing LV networks.

1 Introduction

Electricity demand is rising and is expected to continue to increase because of increased electrical space heating and introduction of electric vehicles (EVs) in urban environments. The bottleneck to delivery is the existing distribution infrastructure, and in particular the buried low voltage (LV) cable network, although these vary significantly from territory to territory. A viable solution to the distribution cable bottleneck is needed to allow the system to cope with the rising energy demands. Replacing the existing buried cable infrastructure in urban environments would be prohibitively costly and disruptive: The average cost of replacing LV cables is £98 000 per km [1]. Considering the total LV circuit length in the UK of 328 038 km [1], replacement costs are prohibitive and unrealistic, which presents a major barrier to increased electrification.

As utilities move towards smart grids, features desired are reliability, flexibility, efficiency and load adjustment [2]. More fundamentally, voltage level regulation may arise depending on the location and the penetration level of distributed generation on the network: Voltages can exceed the statuary limits and can cause problems to customers [3]. For example the unpredictable power output of photovoltaic generation (PV) during the day can cause reverse power flow from the LV to the MV side. This reverse power flow can affect voltage levels, online tap changers, automatic voltage regulators and lead to excessive power losses [4]. Moreover phase imbalances can occur if the PVs are not equally distributed along the network which can increase return currents and losses. A key benefit to converting the distribution network to direct current (DC) is that it will readily allow bi-directional power flow allowing renewable source connection and avoid phase imbalances present under alternating current (AC). The absence of reactive power under DC, will also improve the stability of voltage levels under high penetration levels of renewable sources. Under AC, reactive power does not transfer any useful energy and increases circulating currents in the network, increasing losses and reducing the efficiency of the system therefore reducing losses may also become an economic imperative. In the UK, Ofgem statistics show that distribution network operators have an annual 5.8% loss which amounts to 18 777 GWh lost in the UK distribution network each year [5]. These losses translate to higher prices for the end consumer, and a requirement for more generation.

A further aspiration of DC LV networks is that by using smart-grid functionality to vary the voltage levels around the network, and consequently distributing the load more evenly, also increases the flexibility and the reliability of the network. In particular control of power quality would improve the life-expectancy of primary plant. At present the increased use of inverters for PVs for example may increase harmonic content, adversely affecting the power quality under AC.

It is likely that both capital cost and the operational losses associated with power electronic conversion devices needed to run a DC network will fall over the coming decades [6]. This cost reduction will be driven by needs of higher voltage networks. In any case, the motivation for considering DC in the home and LV distribution network is driven by cost and capacity rather than loss, and is regarded as a long-term aspiration.

Several studies looking at existing infrastructure have previously proposed that the change from low voltage AC (LVAC) to low voltage direct current can substantially increase the power capacity of a distribution system as well as minimise losses, especially in a network containing distributed generation [7–9]. Energy storage and the increase in renewable generation penetration will benefit from a DC network by the reduction of complexity and the fact that they are already run on DC. Elimination of the DC–AC–DC conversion currently used by renewables and distributed generation will minimise losses in the network. It is estimated that this conversion has losses in the range of 2.5–10% [10]. Charging of EVs in the typical AC distribution network will incur further losses given the AC–DC conversion needed to charge the batteries. Domestic appliances such as LED lighting, PC/laptops, mobile phones/tablets are increasingly run on DC. Non-switched-mode power converters used by such appliances can have an efficiency of as low as 40% [11]. A single DC–DC domestic converter connected to a DC distribution network would decrease those losses. Furthermore reduction in number of inverters on the network can decrease harmonic content and associated damage to sensitive equipment [12].

Cables in the UK AC network operate at 325 V peak. As a result it might be assumed that the cables can be run at 325 V_{dc}. Furthermore, these cables are rated at 600/1000 V_{rms} (phase to ground/phase to phase), considerably higher than the present operating voltage. Running these cables at their rated voltage can further increase the power capacity of the cables. Operating an existing LVAC cable under the DC voltage of magnitude equal to the peak AC magnitude gives a theoretical maximum power capacity of $\sqrt{2}$ times that of an AC system. This makes the standard assumption that the AC rms current creates equivalent heat to the same value of DC current, and that value is limited by the thermal design and installation of the cable. Increasing the AC voltage will increase power capacity but will never exceed the power capacity achievable under a DC voltage equal to the peak AC voltage. Increasing the AC voltage furthermore increases dielectric losses. Such losses translate to heat generation which also may age the cables faster. The relative reliability of a DC system running at the peak AC voltage is not known. This uncertainty is an issue since improved reliability is one of the core principles of Smart Grid operation. Clearly increasing the AC or DC voltage creates similar reliability issues.

Exceeding the cable current rating will allow for a higher power flow but in turn make the cables run hotter. This might be a plausible scenario given that the environment the cables are exposed to may be more accurately engineered than was the case for the more generalised and conservative original installation specifications. Several environments might possess better cooling properties than the ones used in rating the cables. This requires careful analysis of the thermal properties of the cables and their respective environments as well as the impact this will have on the life expectancy and reliability of the cables. Given the large variations in environment properties (i.e. local soil and ground conditions) and the vast complexity of a distribution network this might not be the best route to a solution, and some thermal bottlenecks are inevitable.

To get a deeper understanding of the benefits and limitations in converting to a DC network, the current topology of the distribution network and the resulting limitations are investigated in this paper. In particular issues which may inhibit conversion to DC are identified. The structure of the AC distribution network is examined and its main constituents are outlined, focusing on cables, network connections and local power demand. Subsequently we propose configurations for implementation of DC in the existing AC cables for both 3-core and 4-core cables and identify the benefits and limitations of each configuration. Finally consideration is given to potential infrastructure changes necessary for DC implementation including replacing cables, joints and linkboxes.

The present study therefore considers the practicalities of converting an existing buried LV AC distribution network to function under DC and outlines the various changes needed to accommodate such a change. The potential benefits and limitations of converting the existing network are considered and the areas needing further research are identified. Here, because of the diversity of existing low voltage network configurations and components, we focus on typical UK networks.

2 AC distribution network

The UK distribution network mainly consists of three AC operating voltages: 33 kV, 11 kV and 400 V phase-to-phase. These voltages are operated on both overhead lines and underground cables. This paper considers the 400 V part of the network that operates on underground buried cables. This decision is based on the fact that the amount of underground LV cables is double in length compared with the MV network and the LV network is more complex and has many more connections (service cables) compared with the MV network. As a result, replacing the LV network will be more costly and time consuming. In this section we focus on cables, network connections and the power capacity of several parts of the UK distribution network to identify where any potential bottlenecks might rise in the existing AC network when energy demand rises.

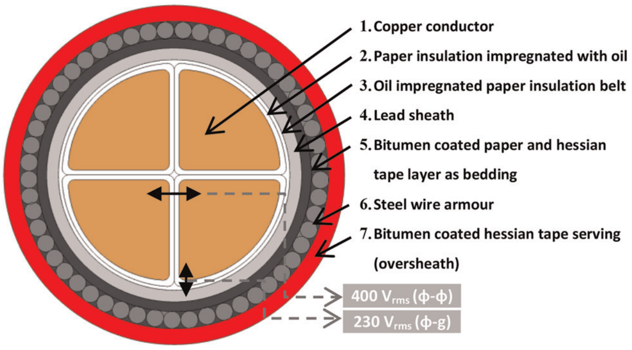

Fig. 1 *4-core (600/1000 V) paper insulated cable*

2.1 Cables

The most common cables installed in the UK LV distribution network before the 1970s were the BS 480 and the BS 6480 paper insulated lead covered (PILC) 4-core belted cable shown in Fig. 1. This cable is rated at 600/1000 V (phase to ground/phase to phase) and consists of four copper conductors, three for the live phases and one for the neutral. BS 480 cables were rated at 660/1100 V. Paper insulation is applied to all conductors and in the case of a belted cable design; an extra shared layer of insulation exists around all the conductors. The cable has a lead sheath which is covered with either steel wire or tape armour to provide stiffness and protection. The outer layer is the oversheath (jacket) which is usually made of PVC or bitumen. The neutral is electrically separated from the earth which typically is connected to the sheath and armour wires.

Since the 1970s, XLPE insulated cables have generally been used in any extensions or new circuits. These can either be 3-core or 4-core. The 4-core cables are used only for repairing or replacing old PILC cables already in service. The most common 3-core XLPE cable used in the UK is the BS7870 cable. In these cables the neutral and earth are combined eliminating the need for a separate neutral conductor as seen in the paper insulated cable. These cables are commonly referred to as 'main' cables. All customers and smaller parts of the network are usually connected to the main cables. These form the backbone of any distribution network.

Using geographic information systems (GIS) data provided by Electricity North West it was possible to extract information on several urban residential networks in the North West of England. All the networks used in this study represent parts of these distribution networks in the North West. It was observed that the majority of LV cables present in the ground today still are paper insulated cables. Fig. 2 shows the main cable types of one such distribution network. Using data from several distribution networks other types of paper cables present in the UK distribution network can be found: Those are shown in Table 1. The 2-core cable is the 'service' cable, connecting customers to the network and is the

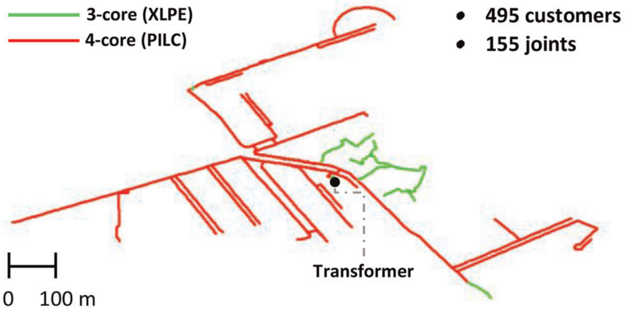

Fig. 2 *Main cables in a typical UK distribution network*

Table 1 Other Paper insulated cables in the UK LV distribution network

Cable type	Conductor arrangement
5-core	Three phases + Street light + N
3-core	Two phases + N
2-core	One phase + N

most common service cable in the distribution network running at 230 V phase to ground.

2.2 Network

In the UK there are three types of system connections between the supply distribution transformer and the consumer. These are the terra terra (TT), terra neutral-separate (TN-S) and terra neutral-combined-separate (TN-C-S). These are illustrated in Fig. 3.

In an TT system, primarily used where a connection is taken from an overhead line, the supply transformer is earthed locally and the consumer unit is earthed through an electrode buried directly into the ground. The TN-S system is the most popular system connection currently in the UK. It consists of an earthed supply providing an earth connection to the end consumer unit. New systems installed the UK will employ a TN-C-S connection where the neutral of the supply is used as the neutral and earth combined [13]. Underground cables are mostly used for the TN-S and TN-C-S systems.

The LV distribution network is a 400 V three-phase system. All the main cables are connected on the transformer feeders in the substation. Residential premises are usually connected to the main cables with a single phase at 230 V phase-to-ground. When more power is required, a three-phase connection is used running at 400 V. Depending on the topology, several premises are evenly distributed along a cable route as shown in Fig. 4: however this is not always the case. On several networks examined, the distribution of phase connections on a single feeder is uneven. Table 2 shows some examples.

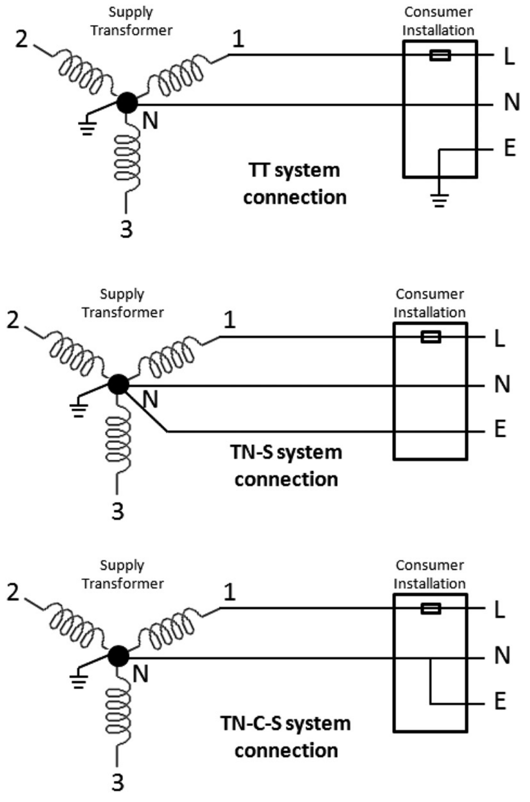

Fig. 3 *System connection configurations*

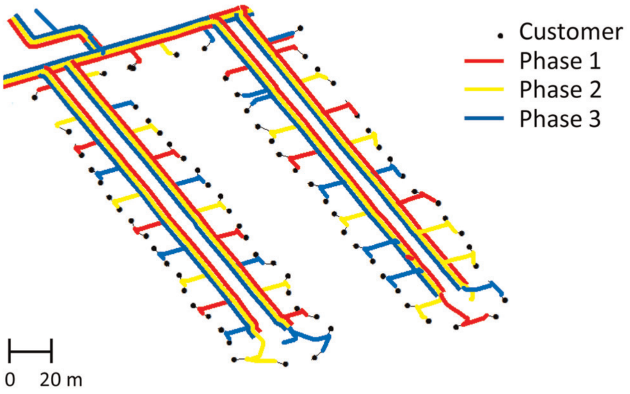

Fig. 4 *Distribution of loads along the three phases on a section of a UK distribution network*

A simplified power flow diagram is shown in Fig. 5. Phase imbalances introduce an increase in return currents, increase system losses and increase voltage imbalances. Careful planning is needed when connecting customers to each phase on the main cable to ensure optimal system performance.

The system currently runs under AC thus all the voltages mentioned are RMS voltages. Each phase in the LV network peaks at a nominal 325 V phase to ground. An increase in power transfer through these cables can only be achieved by increasing the system voltages since the current is limited by the thermal ratings of the cables.

TN-S systems usually use a PILC 4-core belted cable and TN-C-S systems use 3-core XLPE cables. However, many variations in

Table 2 Number of customers connected on different feeders

Feeder	Phase 1	Phase 2	Phase 3
1	30	20	21
2	72	80	68
3	17	32	23

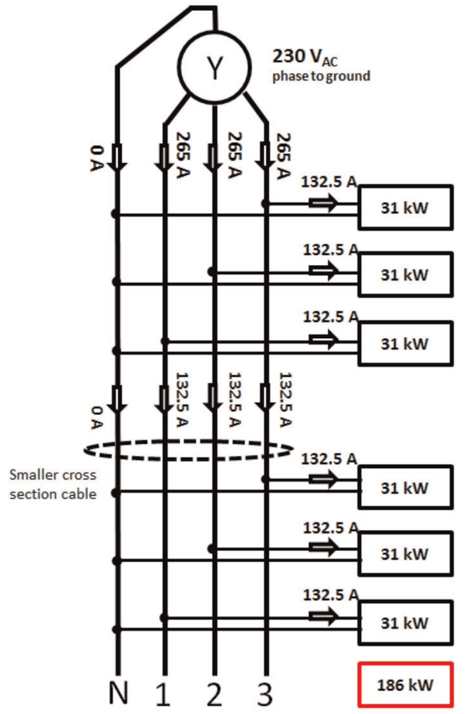

Fig. 5 *Connections along a mains cable with balanced power consumption*

design are deployed and are present in any network. The characteristics of these cables are further discussed in the next section.

It is clear that local practices must be understood in detail before analysis are generalised and assumed to apply elsewhere. The types of cables used in the network might be known, but it is very difficult to know all the topologies employed across the whole of the UK since the network consists of hundreds of thousands of kilometres, and engineering practices vary in different regions with various network operators and historical practices. Extensions to the network and new connections are carried out all the time. This increases the complexity in deciding if a network can be beneficially operated under DC, and makes generic optimisation unlikely.

2.3 Power demand

The rise in energy demand and the overloading of the current network in the future is unavoidable. Anticipated bottlenecks can be predicted by analysing the existing power flow in different parts of the network. Statistical methods can be used to estimate the average power consumption in domestic premises. The CREST Tool was used to estimate the average load profile for 2000 customers shown in Fig. 6 [14]. The month of January was selected since it has the highest energy demand. The tool randomises the type of consumer, appliance use and occupancy status.

The occupancy statistics were taken from the Office of National Statistics [15]. The results shown in Fig. 6 are very close to the Elexon load profiles which use actual 30-min interval data taken directly from energy suppliers [16]. There is a small discrepancy on the graph in the early hours of the day and this is because of the way the CREST tool operates, which assumes that all appliances are started at 00:00. The most important part for this study is the peak load which is around 850 W per customer. This does not consider economy-7 customers that use storage heaters. The economy-7 tariff is used by UK suppliers providing cheaper electricity at off-peak hours to customers.

Estimating the loading of cables requires a power flow simulation of the entire LV distribution network. A simplified loading scenario using the statistically derived peak average demand is shown in Fig. 7. Using the current rating of each cable it is possible to estimate the limit of how many customers can be connected. Using the GIS data the customers currently connected on the cables were determined and plotted in Fig. 7. A unity power factor was assumed.

Six main cables were picked in random to show the variation of cable loading in different parts of a UK distribution network. Each set of bars on the graph indicate the loading on each of the three phases in the cables.

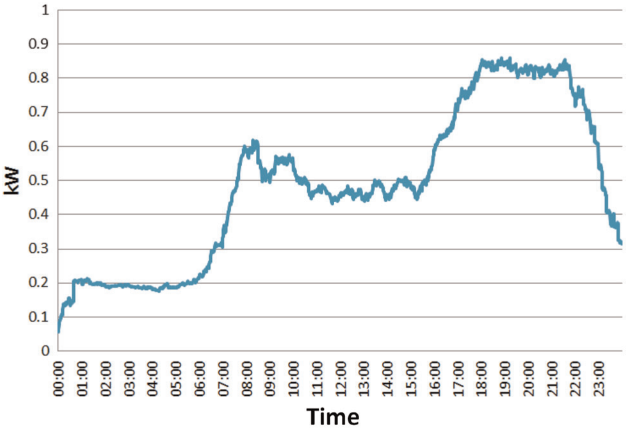

Fig. 6 *Average power demand of 2000 UK households in January*

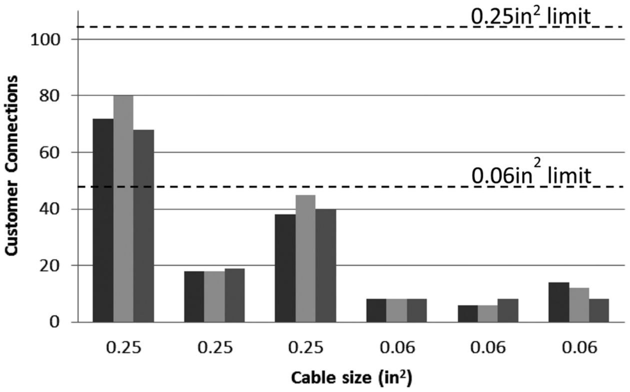

Fig. 7 *Loading on various cables per phase, in a UK distribution network*

Imperial units are used here since the UK started converting to a metric system after 1965. These cables were installed before that date

It is observed that highest loading occurs on the large area cables. These cables are usually loaded to 75% of their capacity. The smaller 0.06 in^2 main cables that most customers are connected to are relatively under loaded to around 15–30% of their rated capacity. The networks analysed were mainly residential networks only, consisting of domestic customers. Distributed generation combined with EVs will certainly increase the power flow in these LV distribution cables. An EV charging station power demand can vary from 3.3 kW (equivalent to four average customers at peak load) for slow charging to 60 kW (equivalent to 71 average customers at peak load) for rapid charging [17]. Even when using the slow charging option, the average peak domestic load will change significantly. Similarly the average domestic PV installation can generate up to 3.68 kW of power which will affect the average peak domestic load [18]. Distributed generation combined with EV will certainly exceed the existing cable loading since the average household power demand of 850 W is very small compared with the power flows required for the above. Using some kind of control algorithms to moderate EV charging patterns and PV power injection to the grid, can rectify this problem. Moving the bottlenecks to more accessible parts of the network might be more cost effective. This can be achieved by shifting the power flow to cables that can be more accessible for replacement rather than replacing the whole network. Nevertheless when high penetration levels are reached this will be a serious problem which ultimately will require uprating of the existing distribution network.

From this preliminary study it can be observed that the larger of the main cables are the first ones to cause problems to the network and by just replacing those cables with larger AC cables might be a viable solution which will not require a conversion to DC, but these results are derived from a very small sample of UK networks. A more comprehensive picture is needed to draw more conclusive results.

3 Optimal configurations

Utilising the existing LV distribution network under DC will require changes to the infrastructure. An optimal configuration is required to allow for the maximum power flow possible in the network. In this section, several DC configurations are analysed and their application to the existing AC cables is investigated. Recommendations on how to achieve the maximum power capacity of the network are proposed by means of raising the system voltage and the effective utilisation of the cable conductors.

3.1 Unipolar/bipolar DC systems and cable requirements

The two basic DC connection configurations used in HVDC connections are unipolar and bipolar. In the unipolar case, one

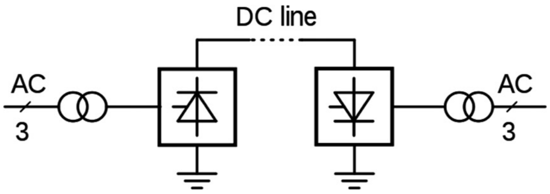

Fig. 8 *Unipolar configuration*

metallic conductor is used to carry the current while the return current is via the earth through special electrodes buried at each side of the line. Fig. 8 shows such an arrangement. Not having a return metallic conductor cuts costs significantly, but a return earth current can cause electrochemical corrosion [19]. An alternative is to use a metallic earth return to carry the return current.

The second major configuration is the bipolar configuration. Two metallic conductors are used to carry current in opposite polarities relative to the ground. This configuration can carry more power with cables rated for lower voltages. A ±500 kV line only requires each cable to withstand 500 kV whereas under a unipolar configuration the cable must withstand 1000 kV for the same power capacity. A bipolar cable can also include a dedicated earth return. One advantage of the bipolar configuration that uses an earth return is that, in case of failure on one of the polarities, the system can still operate at half its capacity. One of the disadvantages of a bipolar configuration is the cost of the extra line. Fig. 9 shows a typical bipolar configuration.

A third, unproven system, patented in 2004, demonstrated a tripolar configuration [20]. This configuration aims to convert existing AC systems to DC utilising all thee conductors in an AC circuit using current modulation to spread thermal load across all conductors. One of the proposed arrangements is to cycle the thermal load between the conductors: One conductor operates at 1.5 times the maximum thermal rating while the remaining two are at 0.75. The high current is periodically cycled through all conductors, evenly spreading the thermal load across all the conductors in the circuit. This allows the full utilisation of all three conductors and can supply more power in case of a fault in one of the conductors. A disadvantage of this configuration is the frequent field reversal which might facilitate insulation ageing. Such ageing results from space charge injection at high voltages, an effect not seen at the low voltages being considered here [21]. No tripole configuration is in operation yet. This configuration might prove useful for HVDC transmission, but the cost of implementation in the LV distribution network might prove to be very high because of the control and power electronics costs.

3.2 Application of DC in existing AC cable networks

The 3-core and 4-core cables present in the distribution network have various conductor sizes. Depending on the power demand, different sized cable is used in different parts of the network. In this study, to simplify the comparison, both types of cables are chosen to have a current rating of 265 A per core. This value is derived from cable standards [22, 23]. These cables are rated at 600/1000 V_{rms} (phase to ground/ phase to phase). Since both cables currently operate at 230 V_{ac} with a current rating of 265 A, total power capacity is 183 kW. This assumes a unity power factor. In reality there will be a power factor decreasing the useful power delivered. The polymeric cable has three cores compared with four in the paper insulated cable. This places the polymeric cable in a disadvantaged position when considering an optimal power capacity under DC.

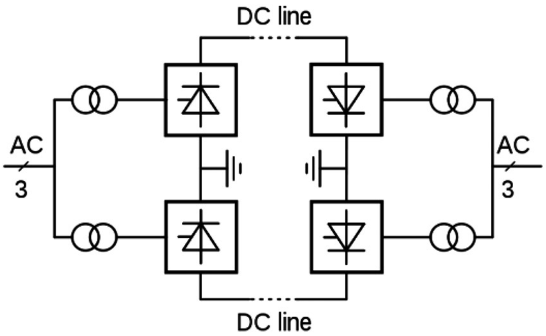

Fig. 9 *Bipolar configuration*

Table 3 Total power capacity of a 3-core cable under different DC configurations

	CORES				
	1	2	3	Total power, kW	Comments
AC	230	230	230	183	cur. system voltage, V_{ac}
	600	600	600	477	max. cable rating, V_{ac}
DC unipolar	230	0	0	61	cur. system voltage, $V_{ac\ rms}$
	325	0	0	86	cur. system voltage, $V_{ac\ peak}$
	600	0	0	159	max. cable rating, $V_{ac\ rms}$
	690	0	0	183	cur. sys. power capacity
	849	0	0	225	max. cable rating, $V_{ac\ peak}$
DC bipolar	230	−230	0	122	cur. system voltage, $V_{ac\ rms}$
	325	−325	0	172	cur. system voltage, $V_{ac\ peak}$
	344	−344	0	183	cur. sys. power capacity
	600	−600	0	318	max. cable rating, $V_{ac\ rms}$
	707	−707	0	375	max. cable rating, $\sqrt{2}V_{p-p}$

*Grey shaded areas indicate when power capacity meets or exceeds the existing power capacity of the cable under AC (183 kW).

In Table 3, different cable configurations are considered for the 3-core cable utilising DC in unipolar and bipolar configurations. To reach the total power achieved under the current AC system voltage of 230 V_{ac} (183 kW), the DC voltage must be raised to 690 V_{dc}. This is a substantial increase from the existing AC peak voltage but these cables were rated at manufacture at 600 V_{rms}, therefore they might be expected to withstand voltages of up to 849 V_{dc} (=600 $V_{rms}*\sqrt{2}$) without compromising their reliability. Operating the cable under this theoretical maximum voltage will yield a power capacity of 225 kW (assuming 265 A per core). One of the cores will not be in use in such a configuration, and instinctively that seems unlikely to optimise the cable utilisation. Using the DC bipolar configuration, the power transfer capability of the existing AC system (183 kW) is reached when operating two of the conductors at ±344 V_{dc}. This voltage magnitude is very close to the peak value of 230 V_{rms}. The maximum theoretical power capacity using the bipolar configuration is reached when the cores are run at ±707 V_{dc} (=1000 $V_{rms}/\sqrt{2}$ V_{dc} phase to phase) of 375 kW (assuming 265 A per core).

Comparing this value with the potential maximum power that can be obtained running the cores at 600 V_{rms} AC, suggests that in a 3-core cable, DC might not be such a good alternative, but compares favourably with running the cables at 230 V_{rms} AC. Under the bipolar configuration, the ±849 V_{dc} (=600 $V_{rms}*\sqrt{2}$) voltage cannot be used because the cable can only withstand 1000 V_{rms} (1414 V_{dc}) phase to phase. Fig. 10 shows how these configurations apply to the 3-core cable.

Running the 4-core PILC cable under DC can significantly increase the cable capacity compared with AC. Table 4 compares the different configurations in both unipolar and bipolar configurations. Fig. 11 shows how these configurations apply to the 4-core cable. Under the unipolar configuration at 344 V_{dc} the total power is matched to that of the cable running under AC (183 kW). Under the bipolar configuration, even at 230 V_{dc} the

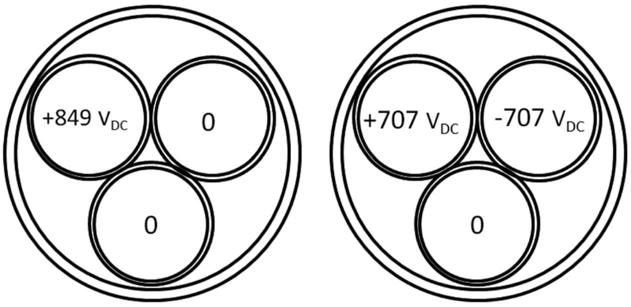

Fig. 10 *3-core cable configurations for maximum power capacity, on the left-hand side unipolar and on the right-hand side bipolar*

Table 4 Total power capacity in a 4-core cable under different DC configurations

	CORES					
	1	2	3	4	Total power, kW	Comments
AC	230	230	230	0	183	cur. system voltage, V_{ac}
	600	600	600	0	477	max. cable rating, V_{ac}
DC	230	0	230	0	122	cur. system voltage, $V_{ac\ rms}$
unipolar	325	0	325	0	172	cur. system voltage, $V_{ac\ peak}$
	344	0	344	0	183	cur. sys. power capacity
	600	0	600	0	318	max. cable rating, $V_{ac\ rms}$
	849	0	849	0	450	max. cable rating, $V_{ac\ peak}$
DC	230	−230	230	−230	244	cur. system voltage, $V_{ac\ rms}$
bipolar	325	−325	325	−325	345	cur. system voltage, $V_{ac\ peak}$
	600	−600	600	−600	636	max. cable rating, $V_{ac\ rms}$
	707	−707	707	−707	749	max. cable rating, $\sqrt{2}V_{p-p}$

*Grey shaded areas indicate when power capacity meets or exceeds the existing power capacity of the cable under AC (183 kW).

total power exceeds that of the AC case. Running the cable at its maximum rated voltage can yield substantially higher power flow under DC. In the unipolar configuration power flow can reach 450 kW and in bipolar configuration this rises to 749 kW. It is clear that the bipolar configuration may provide significant advantages in the 4-core cable. In addition if the two pairs of conductors within the cables are run separately then additional reliability might be achieved.

Power capacity in DC is several times larger than AC depending on the voltage level used. The tripolar configuration would be difficult to implement in the distribution network since there will be a need to modulate current and as a result alternate the voltage levels on each conductor from positive to negative and from higher to lower. Implementation in the distribution network will require each premises connected to the distribution cable to have a means of compensation for the varying voltage levels between the conductors. This might prove to be expensive but with technology advancements in the future the price of the components required for such arrangement might drop to acceptable levels.

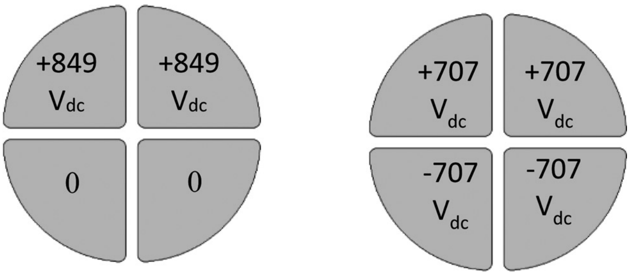

Fig. 11 *4-core cable configurations for maximum power capacity: on the left-hand side a unipolar system, and on the right-hand side a bipolar system*

A clear advantage in power capacity can be observed especially when using a bipolar configuration. Bi-directional power flow will have to be considered to allow the connection of power from distributed generation.

4 System re-cabling

It is to be expected that some parts of an existing distribution network would require re-cabling to accommodate a DC system. Under AC, all the customers in the network are connected to the neutral connection as shown in Fig. 5. Being a three-phase system, the currents cancel out (when balanced) on the return path and consequently the neutral conductor caries no current under normal operating conditions. Unfortunately the phases are not always balanced causing return currents to flow through the neutral conductor. This is still lower than the current through the phase conductors but can generate heat/losses thus increasing the thermal load of the cable. This will not be the case under DC. Current circulates in both positive and negative conductors. Re-cabling will need to take place to evenly distribute the customers along the cores of the cable to evenly distribute the current through all the conductors. Leaving the connections as they are will have the neutral conductor carrying all the return current and thus exceeding its operation levels at several points in the network. Here we identify the re-cabling needed for the main parts of the network for a conversion to DC.

4.1 4-core cables

In a DC network residential customers are distributed along 4-core cables and connected using 2-core service cables. Fig. 12 shows

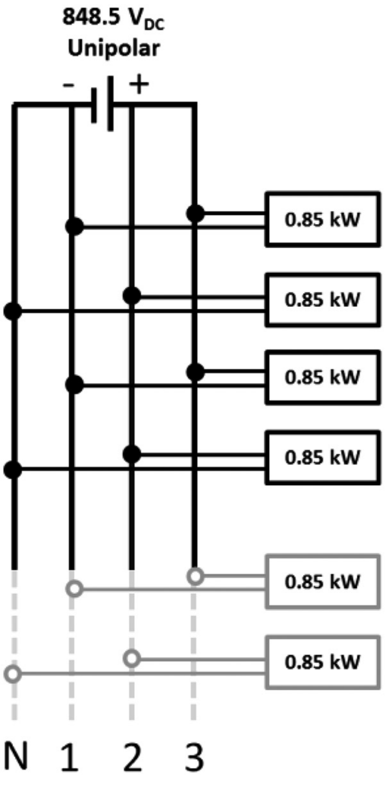

Fig. 12 *System wirings in a 4-core cable*

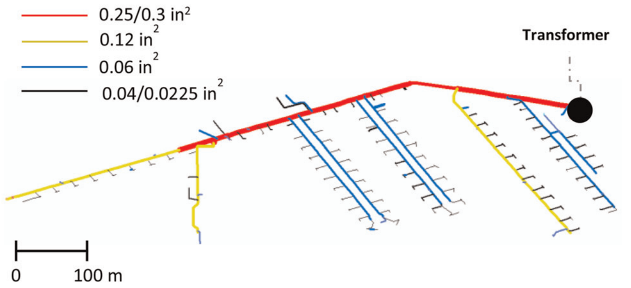

Fig. 13 *One feeder circuit showing different conductor sizes*

the connection of customers along a 4-core cable. The customers will be spread evenly along the four conductors as discussed before. This arrangement will work in cables were all four cores have the same cross sectional area.

Normally the main cables in an AC distribution network have a reduced conductor cross-sectional area after a certain number of customer connections since the current flowing through the cable reduces as shown in Fig. 5.

This reduces the capital cost of the infrastructure. An example of how cable conductor size decreases through a LV circuit is shown in Fig. 13. Incorrect re-cabling for use under DC might cause an unacceptable increase in current flowing in those parts of the line as shown in Fig. 14. In the AC system the current after the dashed region drops to 133 A (see also Fig. 5), whereas in the two DC system configurations, the current rises to 176 A and 265 A, respectively. This must be carefully considered to avoid overloading of the cables. Similarly, the bipolar configuration could be applied to the arrangement shown in Fig. 14, further increasing the power capacity.

Fig. 15 shows two system configurations under DC utilising two conductors in each cable. In these cases the current flowing is the same as in the AC case. By increasing the voltage, higher power is delivered even only by two conductors. With the wiring shown in Fig. 15, some customers could be connected to conductor 1 as well to split the return current. Splitting the return current equally between conductor 1 and 2 can reduce the I^2R losses because of the non-linear dependence on current.

4.2 3-core cables

Utilising all four cable conductors of the 4-core PILC cable will cause incompatibilities when connecting to the newer 3-core polymeric cables. The normal AC practice is to combine the neutral and earth connections from the 4-core cable on the combined neutral/earth connection on the 3-core cable. As a result, a maximum of three conductors can be utilised. Since under DC all three conductors cannot be utilised to carry current, one will be left for fault currents. Fig. 16 shows customer connections on 3-core cables. When the unipolar configuration is used, the third conductor can be used to split the return current.

4.3 3-core cables (2 phases 1 neutral)

The UK LV distribution network does not only consist of three-phase cables. Fig. 17 shows a distribution network that consists of 3-core cables (shown in black) carrying two phases and one neutral. Usually these cables have conductors with equal cross sectional area. These cables are then connected to 4-core three-phase cables (shown in RYB colour).

Fig. 18 shows how the two phase cables are normally connected to the three-phase cables. When re-cabling this part of the network only the 3-core configuration can be used (see Fig. 16). Replacing the 3-core cables with 4-core cable might be required if the 4-core cable decreases in size along the circuit to avoid excessive return currents as discussed before.

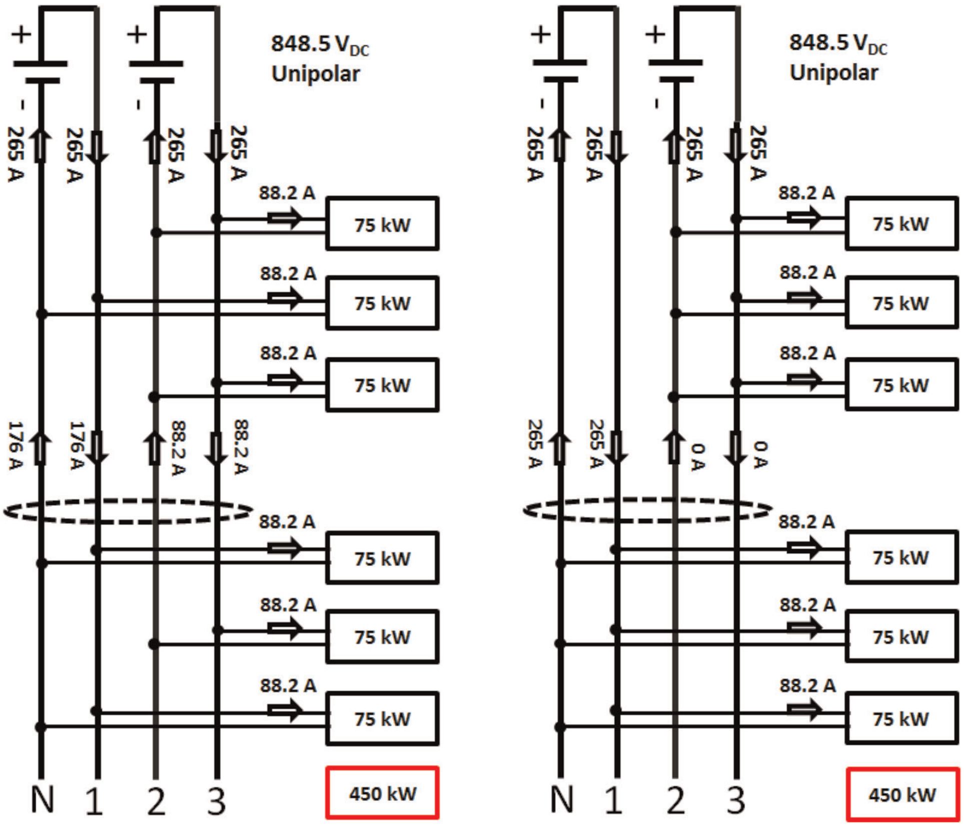

Fig. 14 *System re-cabling under DC utilising four cores*

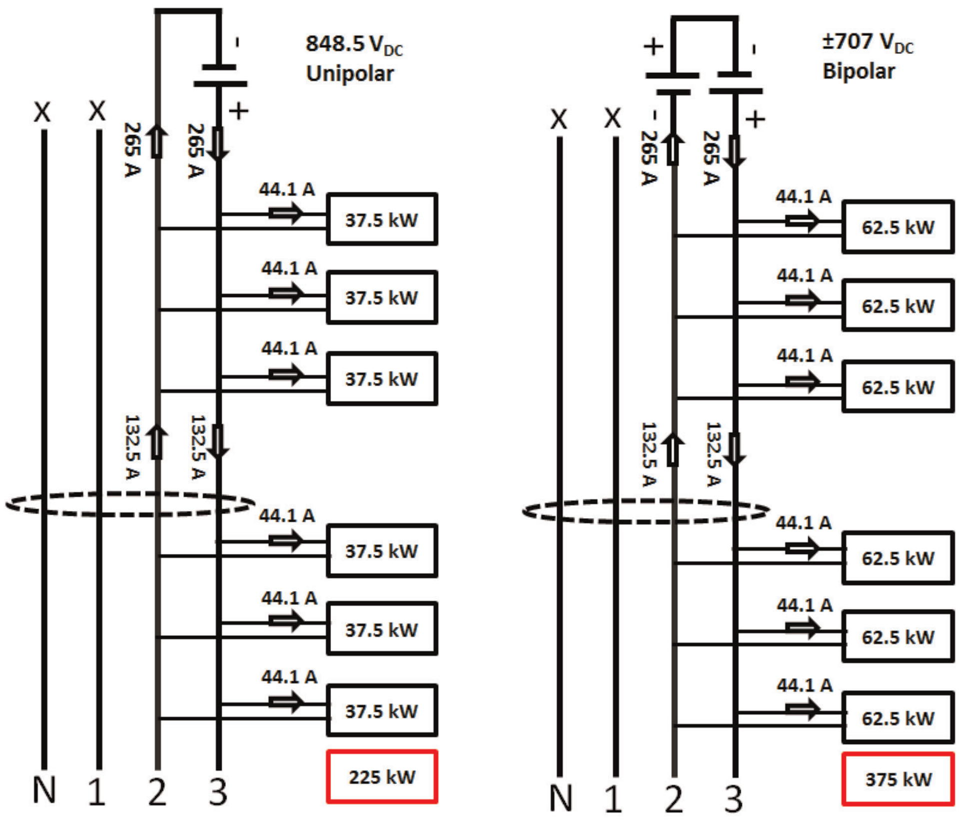

Fig. 15 *System re-cabling under DC utilising two conductors*

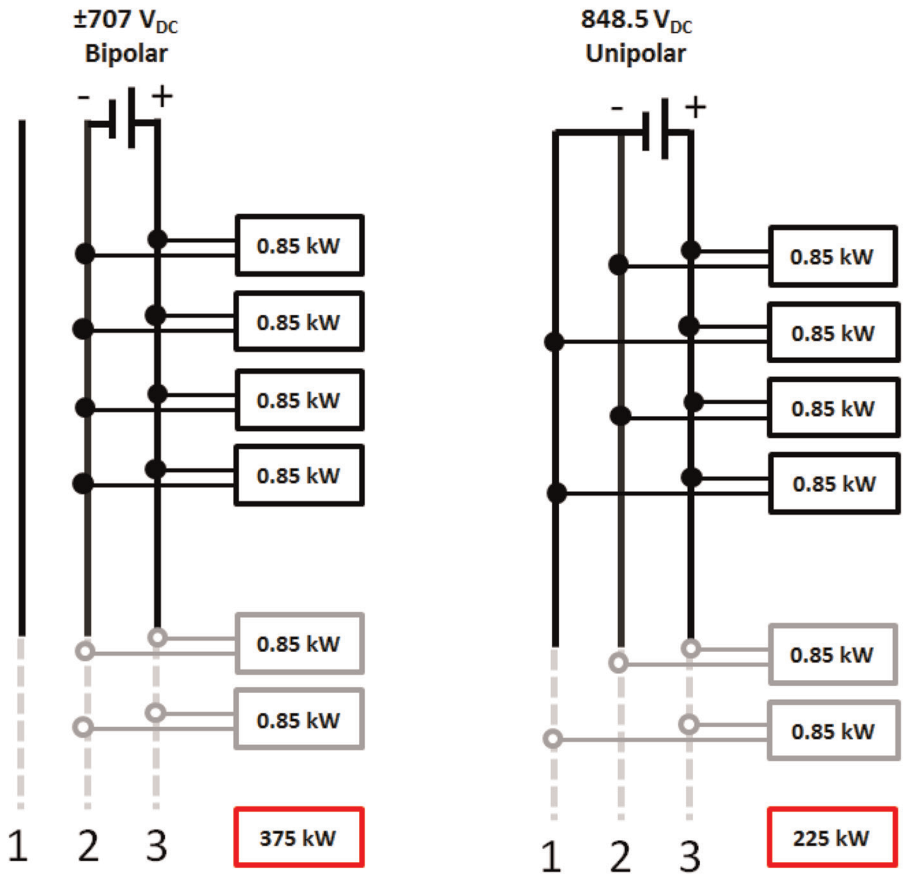

Fig. 16 *System re-cabling under DC in 3-core cables*

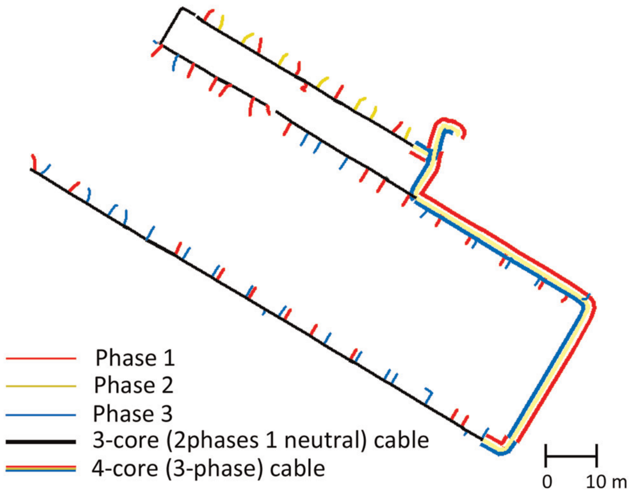

Fig. 17 *3-core (two phases one neutral) cables in a real UK distribution network (black lines)*

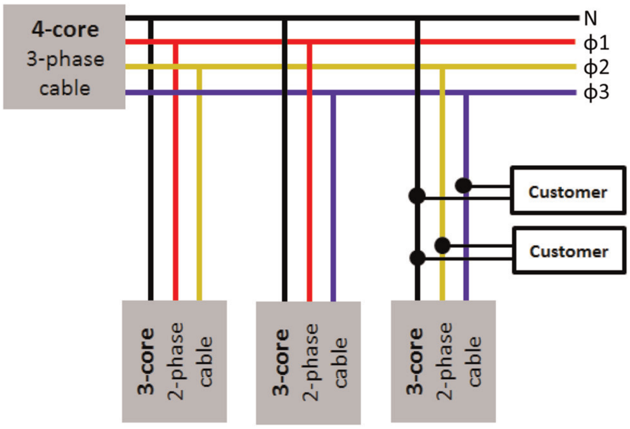

Fig. 18 *Connection of the 3-core (two phases one neutral) cables to the 4-core cables in a real UK distribution network under AC*

4.4 2-core service cables

The majority of service cables are 2-core paper insulated cables consisting of identical cross section conductors. As a result this will not cause a return current problem under DC. Nevertheless these cables will need to be re-connected on the main cable according to the configuration selected.

4.5 Joints

LV networks typically consist of large quantities of several types of joints and connections. As an example the network in Fig. 2 consists of 155 joints (not counting the service connection joints). Table 5 lists the most common types of joints present in the UK distribution networks. Straight joints are normally used when two cable ends need to be connected together whereas branch joints are used when an adjacent connection is required. In a branch joint, the main cable is not split in two. The cable is usually connected on the phases by clamp-on connectors. Cut and Test joints are less common and are used to perform measurements on the network. Pot-end joints are terminations which are placed at the end of the cable length, usually of a main cable to isolate live conductors. Straight and branch joints can be used to either connect cables of the same properties such as size, insulation type and number of phases but also connect cables of different properties. The most common is to connect cables of smaller sizes along the length of the network. Service cables are usually connected using the branch method and can either be single or three-phase. Re-cabling of the service cables will be required again depending on the DC configuration chosen.

Table 5 Joint types in the LV distribution network

Joint type	
Service Cables	Main Cables
service straight joint	main straight joint
service branch joint	mains branch joint
service cut and test joint	main PILC service branch joint
service cable pot ends	main waveform service branch joint
	mains cut and test joint
	mains pot end joint

As discussed before, paper insulated cables can be connected to polymeric cables which might cause incompatibilities depending on the re-cabling configuration chosen. This is because when a paper insulated 4-core cable is connected to a 3-core polymeric cable, the neutral and earth is combined. This prohibits the use of the neutral conductor in the 4-core cable to carry any phase current because of the wire waveform (neutral/earth) in the 3-core cable not being able to carry large amounts of current. Cross-bonding is the practice of splitting sections of a cable run to cross bond the sheaths of the three-phases and connect them to the earth. This helps reduce circulating currents [24]. This is usually applied to MV and HV cables. On the other hand in LV networks physical earthing through a rod or cable is performed at several joints in the network to keep the resistance to earth within the specified limits [25]. This essentially eliminates the usage of the neutral conductor in those parts of the network to carry any useful power. Test and pot-end joints will not require any reconfiguration if DC is to be adopted in the network. Joints are rated at 600/1000 V_{rms} therefore the discussed cable configurations apply, but the quality of such joints in the wider network would need consideration if the voltage levels where increased significantly. Indeed, any concern regarding reliability under changing thermal and voltage loads must be extended from cables to joints and terminations.

4.6 Linkboxes

The LV network has linkboxes, which are used to isolate parts of the network in a case of a fault and reconfigure the network to supply parts of the network from other feeders. The cables connected to the linkboxes are adequate in carrying the current to the rest of the circuit. Depending on the selected configuration, rearrangement of the cable connections might be needed inside the linkboxes as well as in the case that the cable size cannot carry the DC return currents. Re-engineering of the linkboxes although is a relatively easy and straight forward process since they are designed to be very easily accessible. Linkboxes are rated at 600/1000 V_{rms} and so do not present a limitation to the upgrades in voltage as considered or from AC to DC.

5 Discussion

The conversion of an underground distribution network to DC will potentially increase its power capacity. To achieve a higher capacity the system must operate at least at the peak voltage of the AC cycle. Furthermore by increasing the voltage to the limit of the cable ratings will further increase the capacity. Increasing the voltage will inevitably increase the electrical stresses in the cable and may present a reliability problem in aged cables, especially in cases where moisture is already present in the cable [26, 27]. It has been shown that the bipolar configuration can carry more power in both 3- and 4-core cables making it the better choice.

Converting the distribution network to DC must be considered in the context of system reliability. In particular cables and joints which have been pre-aged in an AC network require consideration. UK LV

Table 6 Overview of the possibilities and drawbacks of the transition to DC

BENEFITS		
power capacity	• A DC bipolar configuration at ±707 V_{dc} can provide a theoretical 300% increase in energy flow compared to 230 V_{ac} and a 57% increase compared to an uprated 600 V_{ac} system. • The resulting network can accommodate a higher penetration level of EVs and PVs.	
reliability	• Thermal issues are no greater for DC than AC systems (assuming same rms current through the conductors as with the AC system). • Existing LV AC distribution cables, joints, linkboxes and terminations are already rated for higher voltages (600/1000 V_{rms}) than currently operate at (230/400 V_{rms}). • Bi-directional power flow presents no phase imbalances, requires no reactive power and so provides better voltage stability.	
cost	• The conversion to DC does not require cable replacement in most cases and allows utilisation of existing cable infrastructure. Replacement of LV cables costs £98 400 per kilometre. (LV cable length in UK is 328 038 km). • Lower power losses in the network (see Reliability). Increasing voltage and lowering current can also minimise losses.	
cables	• Majority of mains cables are 4-core which allow for the theoretical maximum power transfer using a DC bipolar configuration on all cores of the cable.	
DRAWBACKS		Further Research Required
reliability	• HV and high electric field ageing mechanisms tend not to occur at LV and low fields but unknown ageing of cables makes it difficult to predict potential failures. • Moisture in cables can lead to higher leakage current and dielectric losses and even thermal runaway under a higher voltage system. • Corrosion is more prevalent under DC.	• Testing of service aged cable insulation ○ Higher voltage (>230/400 V_{rms}) ○ Moisture diffusion ○ Thermal analysis of stressed cables • Modelling of a cable failure modes: especially comparing the impact of moisture in AC and DC cable systems.
cost	• Dig up will be required at service connections. • Re-cabling parts of the network will incur a cost. • The use of Power Electronics is currently perceived as too expensive. Based on projections this cost will drop significantly. Forecasting this cost is out of the scope of this work.	• Identify where re-cabling is needed through case studies derived from network maps. • Estimation of actual costs of re-cabling/opportunity cost. • Identify when Power electronics will be economically practical based on forecasts.
cables	• Re-cabling may be required to allow equal power flow among the cable conductors. • Networks with a both 3-core and 4-core cables will limit the capacity of the local network. This may require some cable replacement.	• Generate a detailed picture of the UK LV distribution network by analysing case studies.
joints	• Existing joints might not be able to withstand the elevated voltages.	• Testing/simulation of existing joints from the network under DC conditions, and increased voltages.

distribution networks contain cables installed over 100 years ago, implying a high level of reliability under existing conditions. Nevertheless these also have the potential for containing existing defects which have yet to lead to failure. The electrical fields seen by these cables are in reality extremely low, and so would not normally be considered a threat under AC or DC. Studies on the fundamental differences in ageing of cable dielectrics under AC and DC conditions are now being driven by higher voltage (transmission network) applications, and it is necessary to consider the low voltage issues in that context. Since this study considers the use of a higher voltage than these cables currently operate, a deeper analysis of how these cables will behave is now required. A similar issue is whether the joints will be able to withstand the increase in voltage (600/1000 V) proposed for DC. In this case it is likely that there will be a dependence on the craftsmanship of the jointer, a further complication when compared with cables which, although of varied design, are manufactured in a more controlled

Further reliability studies are needed to better understand how the cables will behave under DC in an aged condition, before any conclusive proposals are generated. Testing on actual cable insulation is required under the proposed higher voltages including moisture diffusion and thermal analysis of the stressed insulation. More representative low voltage cable ageing models need to be built since these will be very different from HV cables. The fields in LV structures are too low to generate space charge injection and partial discharges in the normal way, and moisture ingress is likely to be a dominate issue. The effect of corrosion must be also considered since it is several times more severe under DC than AC [28].

System re-cabling will be required in certain scenarios where the existing AC network cannot accommodate the different power flow requirements needed for DC. Carefully optimised network topology is needed to allow the smooth operation of the network and allow for a bi-directional power flow. Dig-up will also be required at the point of connection for most premises to allow for the re-connection, as shown in Figs. 15 and 16 for example. This might be difficult in urban areas, or sometimes where the network is covered by large infrastructure. If such large scale dig-up is required – it may be that complete re-cabling with higher capacity AC cables is the preferred option. A more complete picture of the UK network is now required by analysing in detail illustrative parts of the network.

Old parts of a network might be difficult to map thus making the job of finding the connections cumbersome. Every part of the network will have its own physical characteristics making this even more difficult. If an increase in power capacity is inevitable in the future, even if the network still operates under AC, replacement or installation of new cables will still be required.

At present an AC network consists of ring main units, circuit breakers and transformers which will need to be replaced if DC is to be adopted. Power electronics will replace this hardware. At present the technology of the power electronics is at an early stage and as a result the cost might be prohibitive. Nevertheless given time, a point might arrive that this conversion will be a viable solution to the rising demands in electrical power. The key issue for these plant elements is that they are accessible and so physically easily replaced.

Clearly an evaluation must be carried out comparing the cost in converting to DC to uprating the existing AC network to a higher voltage, and comparing both of these to re-cabling higher ampacity cables. Table 6 gives an overview of the possibilities and drawbacks of converting the LV AC network to DC and outlines the further research required to draw more solid conclusions.

6 Conclusions

Simply raising the AC voltage of the UK distribution network to the cable voltage ratings will increase its power capacity by a factor of 2.5. However in principle converting it to DC will always allow for more power down the network. Increasing the DC voltage using a bipolar configuration is the optimum option, but because of the many cable types and configurations in the network – no one optimal solution can be identified. The existing UK LV distribution system contains a wide variety of legacy cables, some 3 core and some 4 core. Even along a branch of a circuit, conductors are reduced in diameter to match AC power flow requirements whilst minimising capital spend.

The future cost of conversion to DC is currently difficult to determine as the, currently prohibitive costs of power electronics, are predicted to continue to fall. However it is clear that although conversion to DC could be done with existing cables, it would still require reconnection of at least the service connection cable to the main cable, and hence the need for civil works would still be expensive. It appears likely than that, depending on the power demand, an uprated AC system might be generally be the more cost-effective alternative.

Reliability models are needed for LV cables and joints for both AC and DC to better understand how cables will behave under higher voltages before any increase of voltage in the systems is considered.

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