

DC utilization of existing LVAC distribution cables

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Abstract – Low Voltage (LV) AC cables are predominant in distribution networks across the world. The possibility of transforming such networks to DC may hold significant advantages and it is widely being considered. In particular it may allow a greater flow of electrical energy within urban areas, allowing adoption of electrical vehicles and Smart Grid applications. Distribution networks in UK use well established 4-core Paper Insulated Lead Covered (PILC) belted cables as well as newer cross linked polyethylene (XLPE) screened cables. Optimal utilization of existing conductors in the cables is of paramount importance in order to fully take advantage of the infrastructure. DC can be applied using a unipolar or a bipolar configuration. Both configurations possess advantages in different situations therefore both are considered in this study. This paper investigates different scenarios and proposes the optimal configurations for an LVDC distribution network. The implications for optimizing power flow are considered.

I. INTRODUCTION

This work is part of the Top and Tail Project, a collaborative blue-sky project funded by the EPSRC Grand Challenge Programme [1]. The project is focused on the physical infrastructure change in energy networks required to move the UK to a low carbon economy thereby contributing to the UK Governments' target of reducing CO₂ emissions by 2050. The project is divided in to two parts, the 'Top' and the 'Tail'. The former focuses on the Transmission part of the network whereas the latter focuses on the last mile of the Distribution Network. This work reported here is part of the 'Tail'.

The move of the electrical distribution network from the legacy LVAC (Low voltage Alternating Current) system to LVDC (Low voltage Direct Current) poses significant benefits and its practicability is being analysed in this study. Several studies have proposed that the change from LVAC to LVDC can substantially increase the power capacity of the system as well as minimise the losses in the system [2]. Electricity demand is rising and will continue to increase in the following years due to the increased amount of electrical space heating and introduction of electric vehicles (EVs). A viable solution to the problem is needed to allow the distribution system to cope.

Operating an existing LVAC cable under DC gives a theoretical maximum power capacity of $\sqrt{2}$ times that of an AC system. This is due to AC systems being operated at RMS (Root Mean Square) voltage whereas under DC they could potentially run at the AC peak voltage. This assumes that the reliability of a cable under AC is the same as that under DC running at peak voltage. DC also benefits from the lack of skin and proximity effects, and no dielectric losses, leading to lower losses in the system.

Ofgem statistics show that DNOs (Distribution Network Operators) have an annual loss percentage of 5.8% [3]. This translates to 18777 GWh (Giga Watt hours) of energy being lost in the UK distribution network each year. The UK distribution network consisted of around 457,965 km of

underground cables in the year 2000 [4]. Data from the past ten years shows no major reductions in the system losses in that time. These energy losses translate to higher kWh price for the end consumer. A breakdown of electricity prices shows that distribution and supply together account for a 53.5% of the total cost of electricity.

If DC is to be used in the network, the replacement of these urban buried cables does not seem to be the best option either economically or practically. The feasibility of using existing cable infrastructure is discussed in the following sections.

II. THE DISTRIBUTION NETWORK

The UK distribution network mainly consists of three 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 only the 400 V part of the network that operates on underground buried cables.

In the UK there are three types of system connections between the supply distribution transformer and the consumer. These are the TT (terra terra), TN-S (terra neutral-separate) and TN-C-S (terra neutral-combined-separate) and are illustrated in Figure 1. In a TT system, primarily used where a connection is taken from an overhead line, the supply transformer is earthed on site 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 and 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 [5]. Underground cables are mostly used for the TN-S and TN-C-S systems.

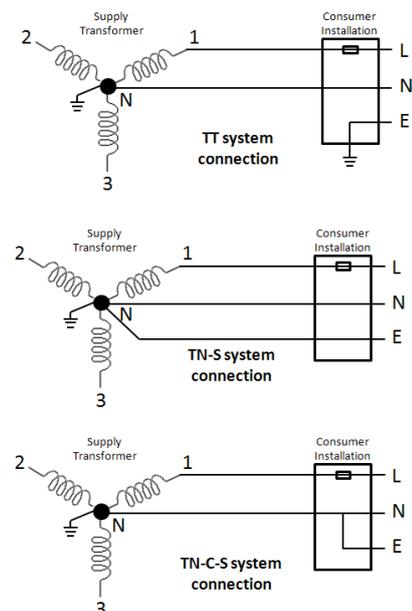


Figure 1 - System connection configurations

The LV distribution network is a 400 V, 3-phase system. Residential premises are usually connected with a single phase at 230 V phase-to-ground. When more power is required, a 3-phase connection is provided. Depending on the topology, several premises are evenly distributed along a cable route as shown in Figure 2. Phase imbalances introduce an increase in return currents, increase system losses and voltage imbalances. Careful planning is needed when connecting end nodes to each phase in order to ensure optimal system quality.

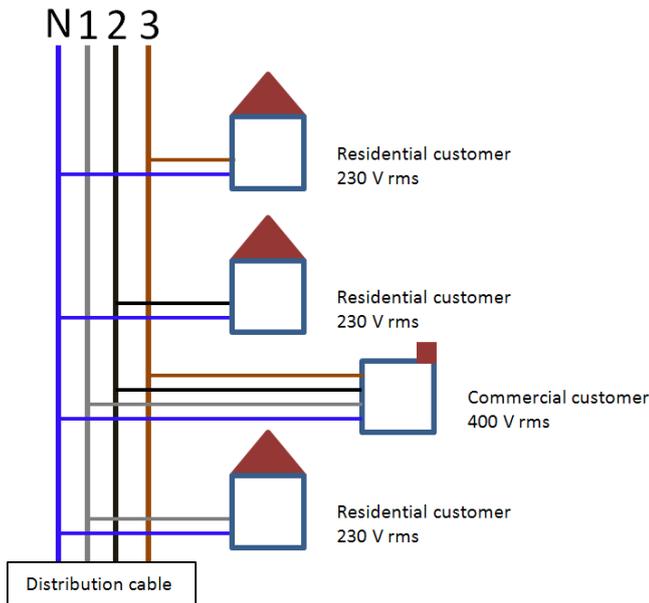


Figure 2 - Connections on a distribution cable

The system runs under AC voltage thus all the voltages mentioned above are RMS voltages and each phase in the LV network peaks at 325 V to ground. When a phase-to-phase measurement is taken, the maximum voltage potential observed is $325 \times \sqrt{3} = 563$ V. 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 [6]. TN-S systems usually use a PILC (Paper insulated lead covered) 4-core belted cable and TN-C-S systems use 3-core XLPE cables. However many variations in design are used and are present in any network. The characteristics of these cables are further discussed in the next section.

The types of cables used in any given network might be known but it is very difficult to know all the topologies employed across the whole of the UK. Extensions to the network and new connections are carried out all the time. This increases the complexity in deciding if the network can be operated under DC.

III. EXISTING CABLES

The most common cable used in the UK LV distribution network before the 1970s was the BS6480 PILC 4-core belted cable [7]. The cable is rated at 600/1000 V (phase to ground/phase to phase). The arrangement of the cable is shown in

Figure 3. This cable consists of four copper conductors, three for the live phases and one for neutral. Paper insulation is applied to all conductors and in the case of a belted cable design; an extra layer of insulation exists around all conductors. The next layer is a lead sheath which is usually grounded. Covering the lead sheath there is a layer of either a steel wire or tape armour used to provide stiffness to the cable and protection. The last layer of the cable is the oversheath (jacket) which is usually made of PVC or bitumen. This type of cable is most notably found in a TN-S system. The neutral is separated from the earth which usually is connected to the sheath and armour wires.

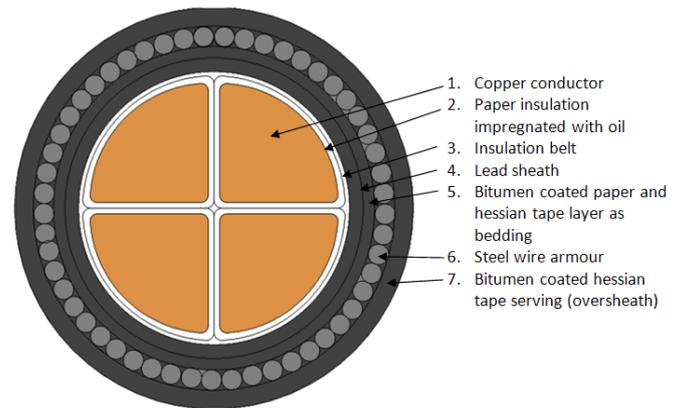


Figure 3 - 4-core PILC cable

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 [8]. This cable consists of three solid aluminium or copper conductors to carry the three phases. Each conductor is insulated with XLPE. The next layer is rubber bedding for the combined neutral/earth copper wires that are shaped to assist jointing and give the cable greater physical flexibility. The final layer is a PVC sheath. These cables are mainly used in a TN-C-S system since the neutral and earth connections are combined therefore there is no need for a separate neutral conductor as in a TN-S system.

IV. POTENTIAL BENEFITS OF DC

Power in an AC system is normally considered to consist of both real and imaginary parts. The Complex power (S) then consists of imaginary Reactive power (Q) and real or active power (P), the vector sum of the two being the Apparent power ($|S|$). In a DC system the power is simply the product of the magnitude of the current and voltage. In the AC case, reactive power does not transfer any useful energy and increases circulating currents in the network thus increasing losses and reduce the efficiency of the system. Operating the network under DC will eliminate this problem.

Cables in the AC network operate at 325 V peak. As a result it might be assumed that the cables can be run at 325 Vdc. This clearly represents an increase in the total power capacity of the cable. Furthermore, these cables are rated at 600/1000 V (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. One option is to increase the AC voltage. This will obviously increase power capacity but will never exceed the power capacity achievable under DC due to the peak voltage advantage discussed previously. Increasing the AC voltage furthermore increases absolute losses. Such losses translate to heat generation which also age the cables faster.

Operating the existing cables under DC eliminates the need of digging up cables and replacing them with new ones. This saves both time and financial investment. One issue of this is the unknown ageing state of the cables in the ground. Raising the voltage might age the insulation faster or even cause electrical breakdowns due to the change from AC to DC. These concerns will be addressed in a separate study.

V. UNIPOLAR/BIPOLAR CONFIGURATION

DC is used extensively in HVDC (High Voltage Direct Current) networks. HVDC links are employed for long distances and are used to transfer power between asynchronous AC networks. The two basic DC connection configurations are unipolar and bipolar. In the unipolar case, one metallic conductor is used to carry the current while the return current uses an earth return through special electrodes buried at each side of the line. Figure 4 shows such an arrangement. The lack a return metallic conductor dramatically cuts costs but can cause electrochemical corrosion. In undersea connections the electrodes can produce chlorine which affects the seawater quality [9]. A solution to this is to use a metallic earth return to carry the return current.

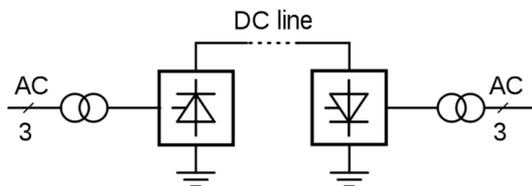


Figure 4 - Unipolar configuration

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. Figure 5 shows a typical bipolar configuration.

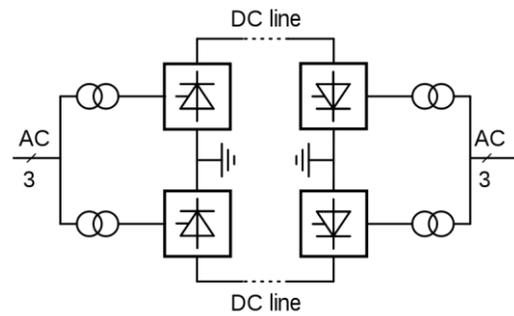


Figure 5 - Bipolar configuration

A third unproven system, patented in 2004, using a tripolar configuration aims to convert existing AC systems to DC utilising all three conductors in the AC circuit using current modulation to spread thermal load across all conductors [10]. One of the proposed setups is to cycle the thermal load between the conductors. One conductor operates at 1.5 times the maximum thermal rating with the remaining two at 0.75 times. The high current is periodically cycled 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. No tripole configuration is in operation yet. This configuration might prove useful for HVDC, but the cost of implementation in the LV distribution network is likely to prove to be too high.

VI. OPTIMAL CONFIGURATIONS

The two cables (four- and three-core) present in the UK distribution network mentioned previously come in various conductor sizes. Depending on the power demand, different sized cables are used in different parts of the network. In this study, to simplify the process, both types of cables are chosen to have a current rating of 265 A per core. This value is derived from tables in the cable standards [7,8]. Under AC the maximum power through both cables is 183 kW. This assumes a unity power factor. In reality there will be a power factor decreasing the useful power delivered.

DC should at least match or exceed the power capacity of the cable under AC in order for it to have some potential value. The polymeric cable has three cores compared to four in the paper insulated cable. This places the polymeric cable in a disadvantaged position when considering an optimal power capacity under DC. In Table 1, different configurations are considered for the 3-core cable utilising DC in unipolar and bipolar configurations. In order to reach the AC total power using DC in unipolar configuration, the voltage should be raised to 690 Vdc. This might seem high but these cables are rated at 600 Vrms therefore theoretically they should withstand voltages up to 849 V ($=600 \cdot \sqrt{2}$). Operating the cable under that voltage will yield a power of 225 kW. One of the cores will not be in use in such a configuration. Using DC bipolar, the AC total power is reached when operating two of the conductors at ± 344 V. This voltage is very close to the peak value of

230 Vrms. Under the bipolar configuration, the 845 V voltage per conductor cannot be used because the cable can only withstand 1000 Vrms (1414 Vdc) phase to phase.

The maximum total power under this configuration is 375 kW. Comparing this value with the potential maximum power that can be obtained running the cores at 600 Vrms AC, suggests that in a 3-core cable, DC might not be such a good alternative. Figure 6 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 to AC. Table 2 compares the different configurations in both unipolar and bipolar configurations. Under the unipolar configuration at 344 V the total power is matched to that of the cable running under AC. Under bipolar configuration, even at 230 Vdc the total power exceeds that of the AC case. It is clear that the bipolar configuration poses significant advantages in the 4-core cable. Power capacity in DC is several times larger compared to AC depending on the voltage level, see Table 2.

The tripolar configuration might 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. Applying this configuration between two substations will be less of a problem. Implementation in the distribution network will require each premise 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.

Table 1 - Core configuration in 3-core cable

	CORES			Total Power (kW)
	1	2	3	
AC	230	230	230	183
	600	600	600	477
DC	230	0	0	61
Unipolar	325	0	0	86
	600	0	0	159
	690	0	0	183
	848.5	0	0	225
DC	230	-230	0	122
Bipolar	325	-325	0	172
	344	-344	0	183
	600	-600	0	318
	707	-707	0	375

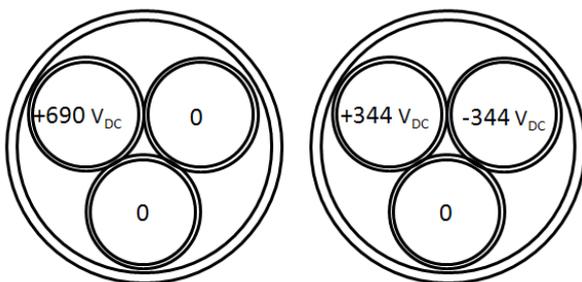


Figure 6 - 3-core cable configurations for maximum power capacity

Table 2 - Core configuration in 4-core cable

	CORES				Total Power (kW)
	1	2	3	4	
AC	230	230	230	0	183
	600	600	600	0	477
DC	230	0	230	0	122
	325	0	325	0	172
	344	0	344	0	183
	600	0	600	0	318
	848.5	0	848.5	0	450
Bipolar	230	-230	230	-230	244
	325	-325	325	-325	345
	600	-600	600	-600	636
	707	-707	707	-707	749

VII. SYSTEM RE-WIRING

The current distribution network will require re-wiring in order to accommodate a DC system. Under AC, all the nodes in the network are connected to the neutral connection as shown in Figure 7. The currents cancel out on the return path, consequently the neutral conductor carries no current under normal operating conditions. Current only circulates in case of a fault or imbalance between the phases. This will not be the case under DC. Current circulates in both positive and negative conductors. Re-wiring will need to take place to evenly distribute the current through the conductors. Leaving the connections as they are will result in over-rated current flowing through the neutral conductor exceeding its operation levels. Figure 8 shows two possible re-wirings utilising four cores in a cable.

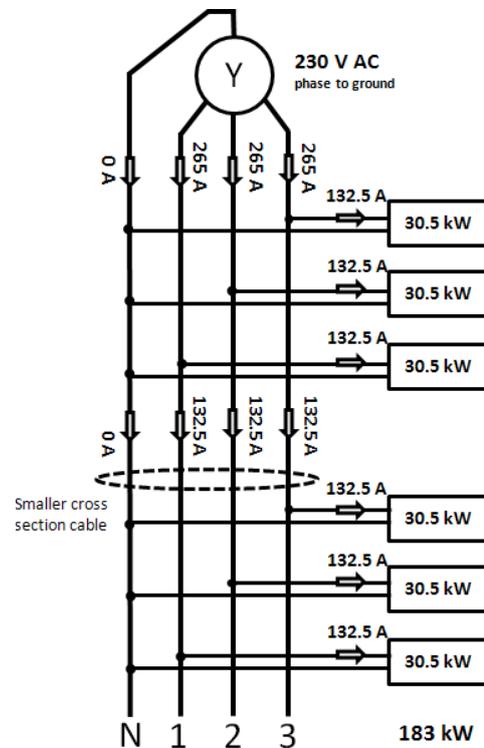


Figure 7 - System wiring under AC

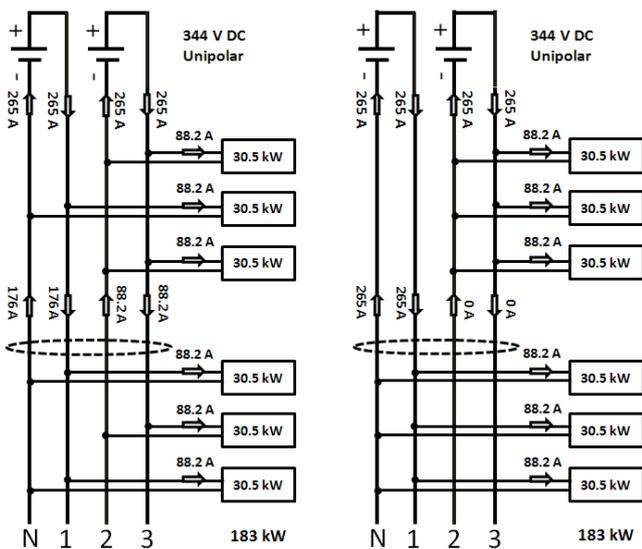


Figure 8 - System wirings under DC utilising four cores

In an AC distribution main line, the conductor cross sectional area can be reduced after a certain number of node connections since the current flowing through the cable reduces as shown in Figure 7. Re-wiring for use under DC might cause an increase in current flowing in those parts of the line as shown in Figure 8. In the AC system the current after the dashed region drops to 132.5 A, whereas in the two DC system re-wirings, the current rises to 176 A and 265 A respectively. Figure 9 shows two system configurations under DC utilising two conductors in the cable. In these cases the current flowing is the same as in the AC case. By increasing the voltage, the same power is delivered by only two conductors. In the configurations shown in Figure 9, nodes could be connected to Conductor 1 as well in order to split the return current. Splitting the return current equally between conductor 1 and 2 can also reduce the I^2R losses.

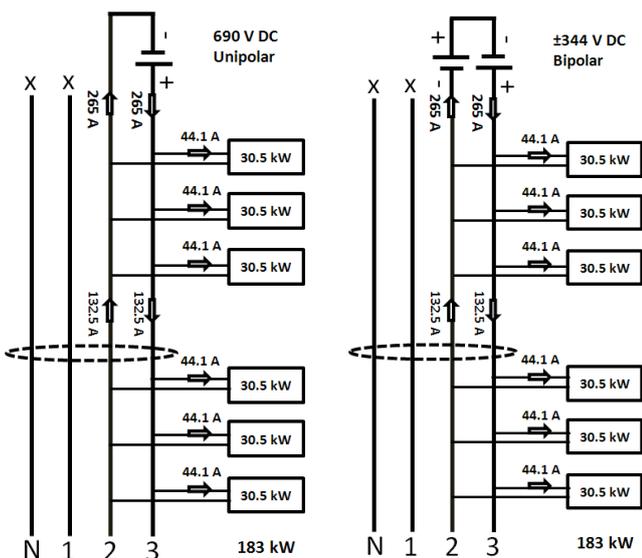


Figure 9 - System wirings under DC utilising two conductors

Utilising all four cable conductors of the 4-core PILC cable will cause incompatibilities when connecting to the newer 3-core XLPE cable. The normal 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.

VIII. SUMMARY AND CONCLUSIONS

Utilising existing LVAC cables under DC may increase the total power transfer in most cases. By increasing the voltage to the maximum rated voltages dictated by the manufacturers, a clear increase in power transfer can be achieved. A major setback for this proposition is the need to rewire all the nodes connected to the network in order to optimise the current flow in the system. This might prove very expensive and time consuming. The bipolar configuration is the most optimal for higher power transfer while keeping the current levels within the rated limits. Incompatibilities might arise when the old 4-core cables are joined with the newer 3-core cables. Careful re-wiring planning will be necessary to avoid any system overloading. These conclusions are based on the assumptions that the cables can withstand those higher voltages. Further studies will focus on the reliability of these cables running under DC and how ageing might affect this. Ultimately this is a dielectrics reliability issue.

ACKNOWLEDGMENTS

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