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THE USE OF INSULATED WIRES MILLIKEN CONDUCTORS IN HIGH VOLTAGE POWER TRANSMISSION UNDERGROUND AC LINES

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ABSTRACT

These last years have pointed out a significant increase of the power that needs to be transported by underground power cables. As a consequence, large cross section conductors, up to 2500mm² are now customarily used.

The CIGRE group B1-03 has completed in 2005 a work that analyses the actual AC resistance of these large cross section conductors as a function of their design.

The authors discuss about the implication of this work on the design of typical high power transmission lines, from the cable production, accessories, unit length, transportation, civil works, and operation.
They sketch the limits of use of each conductor design as a function of the projects key parameters.

They give the AC resistance measurement results on some conductors of different designs.

KEYWORDS

HIGH VOLTAGE, CONDUCTOR, POWER LINK

INTRODUCTION

These last years have pointed out a significant increase of the power that needs to be transported by underground power cables. As a consequence, large cross section conductors, up to 2500mm² are now currently used.

These conductors have diameters in the range of 60mm, which is not small as compared to the skin effect depth. CIGRE set up in 2002 a working group B1-03 to assess the AC resistance of large conductors. Its final report was released in 2005 in the Technical Brochure 272 [1]. It showed the interest of Milliken conductors with insulated wires.

We will recall the conclusions of this work and give practical examples of the use of the recommended conductors.

AC RESISTANCE OF LARGE CONDUCTORS

CIGRE WG B1-03 chose a pragmatic approach that is based on measurements. It built the following table:

Type of conductor	k_s Value	k_p Value
For copper enamelled wires and aluminium wires	0.25	0.15
For copper oxidised wires (value based on study for uni-directional only)	0.35	0.20
For inter layer insulated copper.	0.50	0.37
For uni-directional stranding of copper bare wires	0.62	0.37
For bi-directional stranding of copper bare wires	0.80	0.37

The AC to DC resistance of a conductor is given by the formula :
$R=R'(1+y_s+y_p)$

$$y_s = \frac{x^4}{192+0.8\,x^4} \quad \text{with} \quad x^2 = \frac{\omega\mu}{\pi.R_{dc}}.k_s$$

$$y_p = 2.9\frac{x_p{}^4}{192+0.8\,x_p{}^4}\left(\frac{d_c}{s}\right)^2$$

with $$x_p{}^2 = \frac{\omega\mu}{\pi.R_{dc}}.k_p$$

d_c is the conductor diameter
and s is the axial distance between conductors.

Let's concentrate on the skin effect, as in practical conditions; the proximity effect is smaller than 1/10th of the skin effect.

The authors have manufactured cables of 1600mm², 2000mm² and 2500mm² cross section, which are in accordance with the last release of IEC 60228.
The resistance of these cables has been measured using the previously reported method [2, 3]
The samples length is 12m. All conductor wires are connected together at each end, the distance between voltage probes is 8m.

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The following table gives our measurements, at 90°C, as compared to IEC and CIGRE formulas.

$\frac{(AC_{90}\text{resistance})}{(DC_{90}\text{resistance})}$	**CONDUCTOR TYPE**								
	Round			Standard Milliken Bi-directional stranding			Enamelled milliken		
	IEC	CIGRE*	Authors	IEC	CIGRE	authors	IEC	CIGRE	Authors**
1600mm²	1.30	na	1.31	*1.07*	*1.20*	***1.25***	*1.07*	*1.025*	***1.04***
2000mm²	*1.40*	na	1.45	*1.11*	*1.30*	***1.35***	*1.11*	*1.04*	***1.04***
2500mm²	*1.53*	na	1.61	*1.16*	*1.41*	***1.45***	*1.16*	*1.06*	***1.065***

*out of the scope of WG B1-03
** authors precision of results is ± 0.05 (the main cause of error is the conductor temperature precision and homogeneity).

The table shows the quality of the CIGRE WG work. Calculated skin effect is very close to measurement. The IEC formula when applied to the large cross section gives optimistic results. IEC 60287-1-1 specifies that the given parameters are valid for cross sections less than 1600mm².

COMPARISON OF DIFFERENT SPECIFICATIONS

To evaluate the benefit of improved conductor construction; it is necessary to compare the performance of standard design (bare copper wire) and insulated wire design (enamelled wire in this study) cables.
The cables are 400kV cables, XLPE insulated, butt to butt welded aluminium laminate screen, HDPE oversheath.
Such a comparison will serve as a guideline throughout this paper and for each feature the main conclusions shall be drawn.

Table for comparison

In the following table are given the main characteristics and performance in the same laying arrangement of different cross section cables.
The conductors are supposed to be with a Milliken construction, bi-directional stranding, with 6 segments.
The calculation of the a.c. resistance of conductor have been based on the skin effect and proximity effect coefficients k_s and k_p as recommended in the CIGRE Technical Brochure n° 272 [1] i.e.:

- k_s = 0.8 and k_p = 0.37 for bare copper conductor
- k_s = 0.25 and k_p = 0.15 for copper enamelled wires

The laying arrangement is the same for every cable type:

- Two parallel circuits
- Flat formation, cable spacing: 350 mm
- Burial depth: 1300 mm
- Soil thermal resistivity: 1.0 K.m/W
- Ground temperature: 20°C

Table 1: Raw data

In the following table the “e” suffix stands for enamelled wire i.e. a conductor having in its construction a sufficient number of insulated wires to prevent any electrical contact between adjacent wires. Losses are given at rated current for one circuit.

Conducor area and type	mm²	1200	1200e	1600	1600e	2000	2000e	2500	2500e	3000	3000e
Overall Diameter	mm	117	117	125	125	131	131	140	143	147	147
Weight	kg/m	20,3	20,3	24,85	24,85	29,27	29,28	35,8	36,38	39,7	39,7
Current carrying capacity	A	1208,0	1271,9	1351,0	1463,0	1460,9	1626,5	1558,5	1780,0	1630,0	1907,5
Transmitted power	MVA	836,9	881,2	935,9	1013,0	1012,1	1126,9	1079,7	1233,4	1129,6	1321,5
Losses at maximum current	kW/km	106,9	107,0	109,9	110,2	113,3	113,7	116,0	117,1	118,1	119,1
AC resistance at 90°C	μΩ/m	21,743	19,524	17,501	14,469	15,055	11,928	13,116	9,742	11,916	8,315
Rac/Rdc	-	1,129	1,014	1,215	1,025	1,312	1,039	1,434	1,061	1,554	1,087
length over one drum	m	1150	1150	1094	1094	876	876	550	552	523	523

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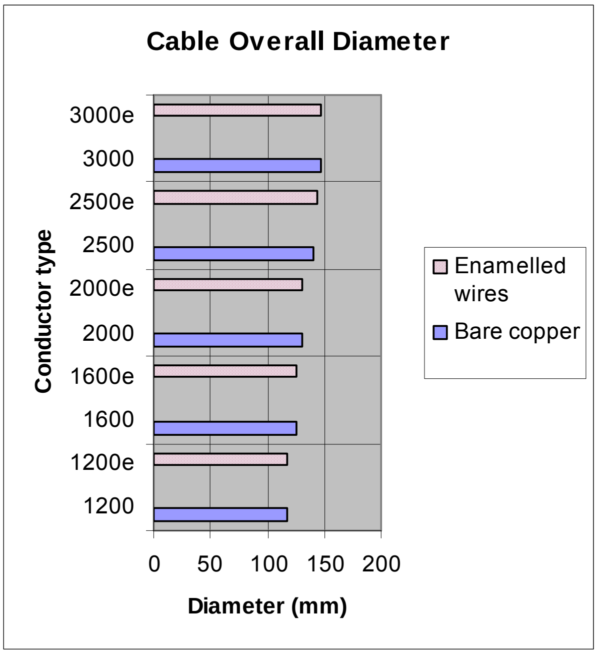
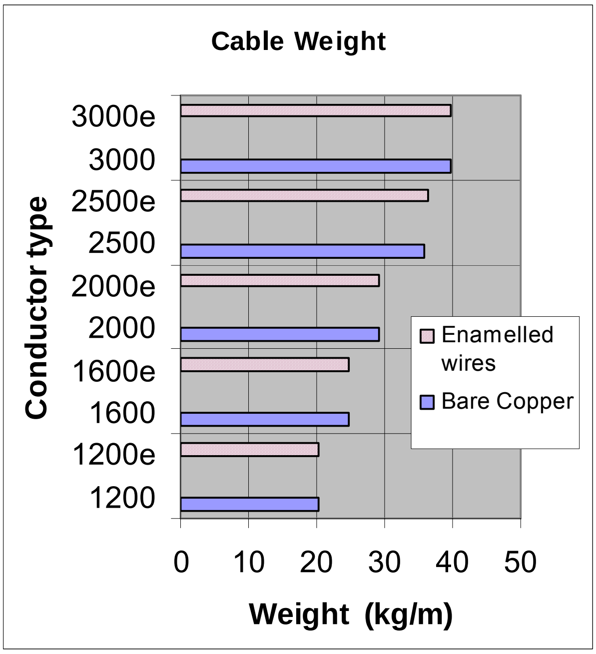
CABLE OVERALL DIAMETER

Except for the 2500 mm² the construction of which is different for the insulated wire type introducing enamelled wires in the conductor does not change the conductor diameter (small thickness of the enamel layer).
This is shown on the following bar graph.



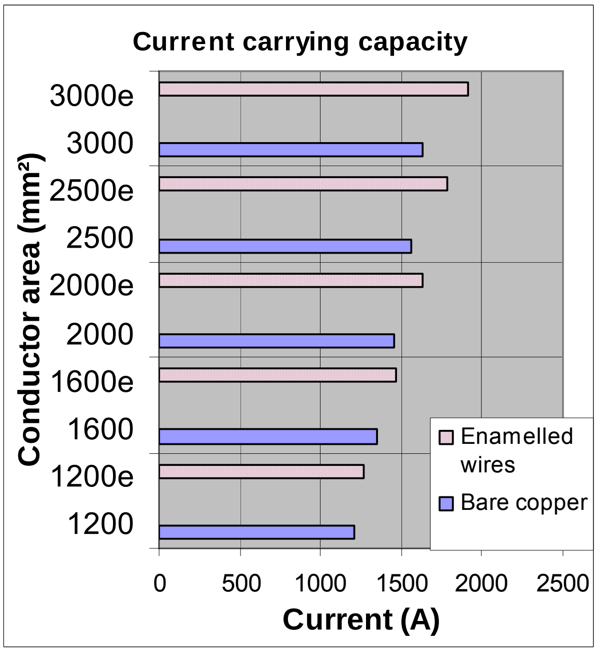
CABLE WEIGHT

For the same reason there is little change in cable weight between the two designs (small weight of the enamel later).



CURRENT CARRYING CAPACITY

This is the most interesting feature of cable with insulated wire conductor.
Due to the lower skin and proximity effect factors the ampacity of the cable with insulated wires is often higher than the one of the bare copper cable with one cross-section higher.
E.g. a 1600 mm² copper with insulated wires cable exhibits a higher current carrying capacity than a 2000 mm² standard cable.
For cross-section lower than 1600 mm² this rule does not apply.
But for all section including 1600 mm² and above the enamelled construction is always better than the bare copper construction with one cross-section upper.



LENGTH OVER ONE DRUM

In order to evaluate the benefit of having a smaller cable for the same current carrying capacity we have compared the cable length that can be accommodated on a typical drum whose dimensions are:

- Flange diameter: 4.5 m
- Overall width: 2.5 m

The barrel diameter “DB” of that drum has been adapted to each cable according to the following rule:

- DB ≥ 20 x cable OD

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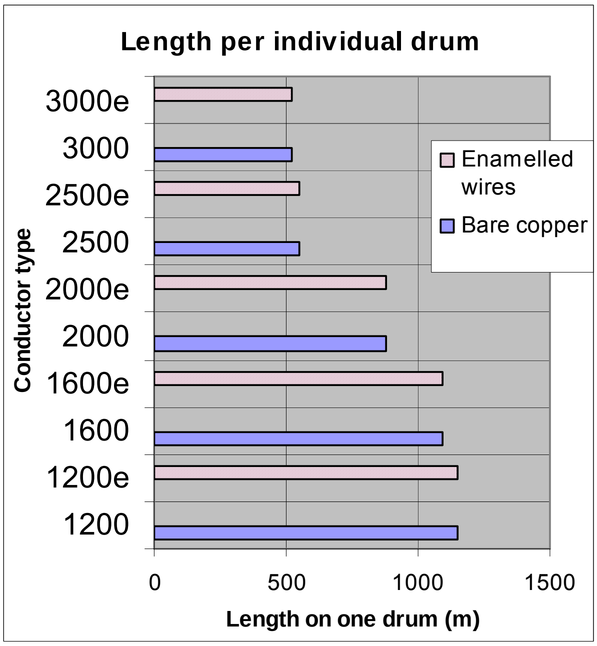
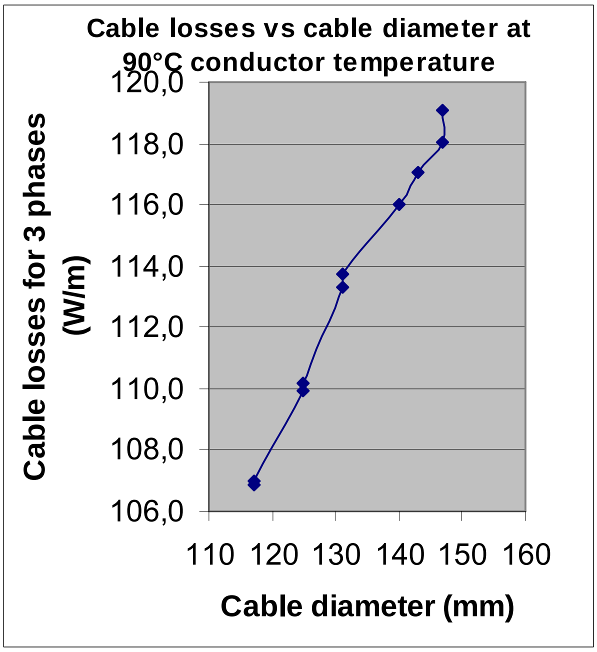


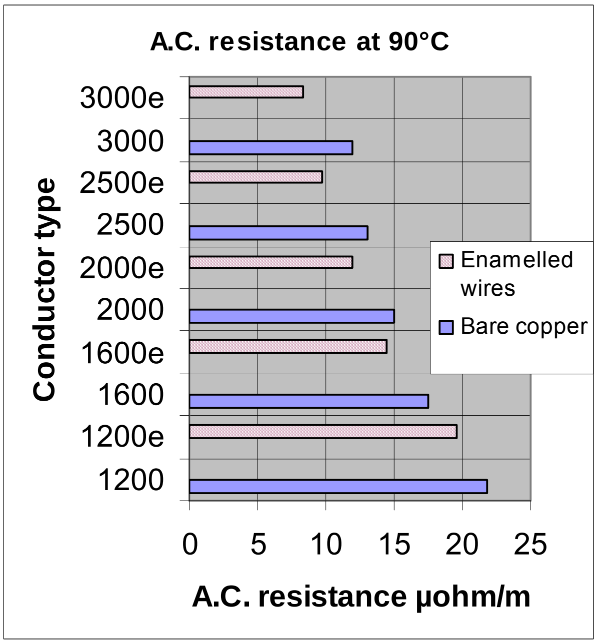
Again there the great advantage of insulated wires is using a smaller cable for the same ampacity.
It allows lengths between joint to be increased by up to 40%.

CABLE LOSSES

In table 1 all the losses are calculated for the maximum permissible current that is to say for the current that lead to a conductor temperature of 90°C. It is remarkable that the conductor losses at 90°C do not vary very much neither with the cable size nor with the current. All cables have very similar thermal internal resistances and the quantity of heat they can dissipate in a given environment is almost constant. In fact it only varies with the cable external diameter.

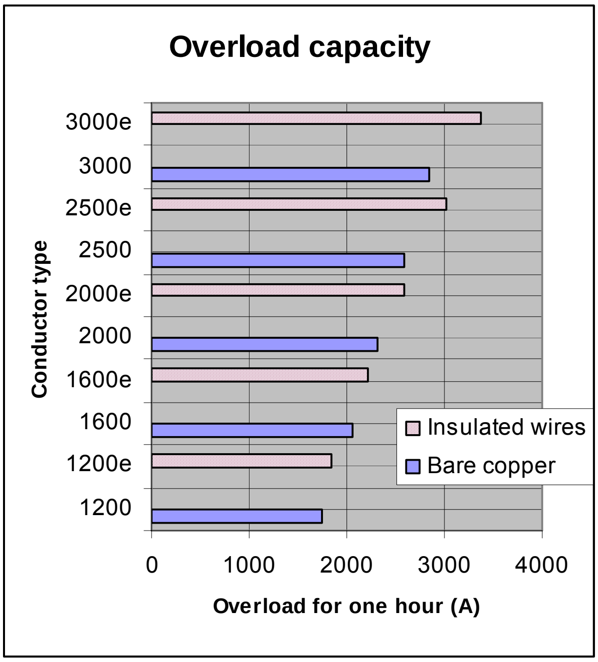


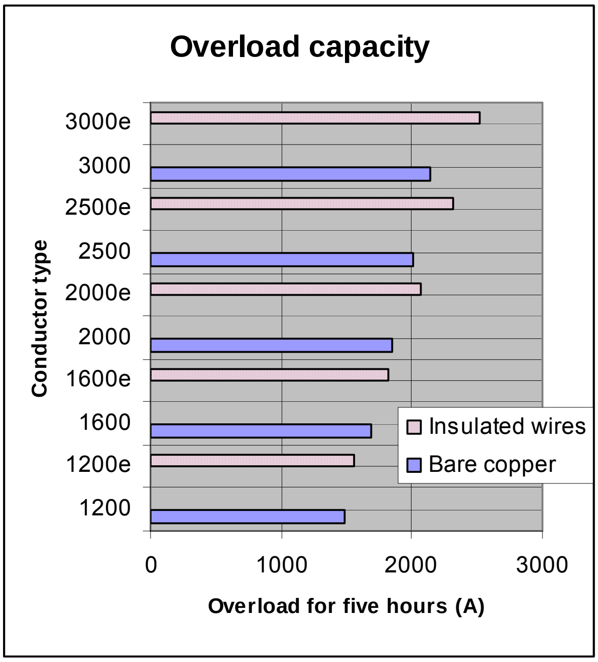
For a given current, the total losses can be reduced by much when using an enamelled wire conductor, in fact almost in the same proportion as the a.c. resistance.



OVERLOAD CAPACITY

One might wonder whether the overload capacity of a cable with insulated wires is as high as the one of a standard cable of same current carrying capacity. Indeed cables with insulated wires being smaller and lighter their thermal capacitance is smaller. However their losses being lower than those of a cable with a standard conductor (with one cross-section bigger) their overload capacity is very close and even better for the very large cross-sections.
This is ilustrated in the two following graphs.

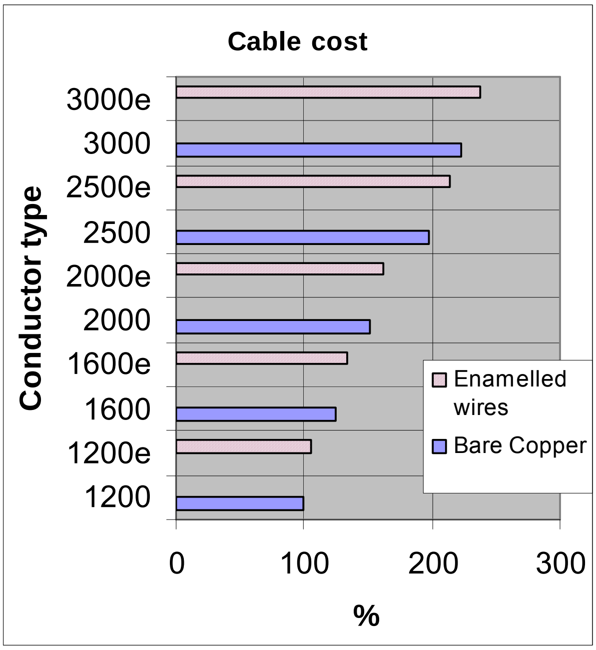




The following hypotheses were taken:
Start from maximum load (90°C at conductor).
Maximum overload conductor temperature: 100°C.
The calculations were carried out according to IEC 60853-2

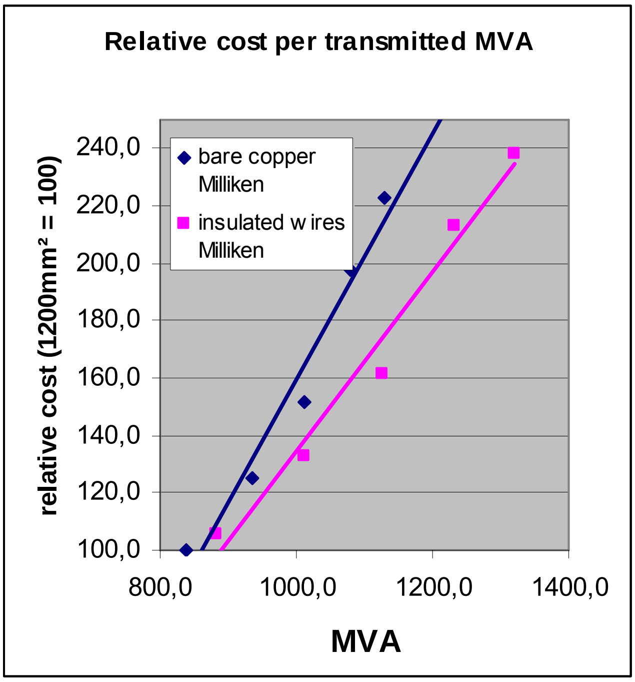
CABLE COST

Cable cost is very sensitive to copper cost and also to the other materials cost. The benefit of the insulated wire technology increases when the raw materials are expensive. This is the case at present time.



In the above diagram it is shown that conductor from 1600mm² to 2500 mm² with enamelled wire are less expensive than one cross-section above cables.
Installation cost per accessory are slightly higher for enamelled conductor because the connection of enamelled wires conductor need special techniques, however this is by far compensated by the lower price of cable and by the reduced number of accessories with is a direct consequence of longer unitary drum length.

The cable relative cost per transmitted MVA show a clear advantage for the insulated wire Milliken conductor design. If the economics of the complete link had been taken into account, including transportation, civil and installation works, the benefit would have been even higher.



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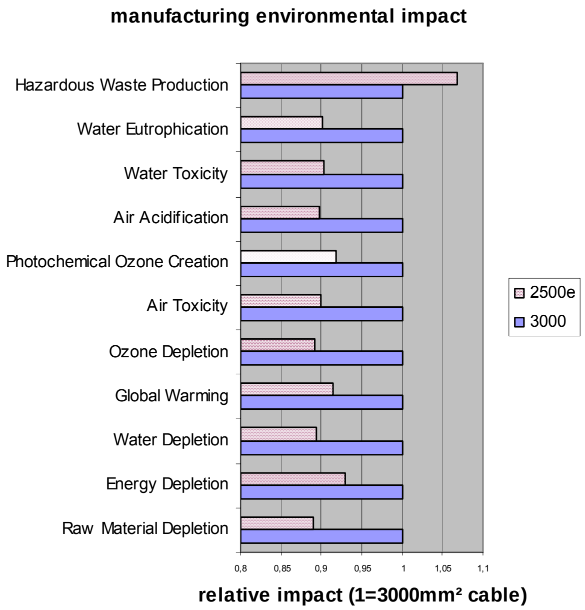
ENVIRONMENTAL IMPACT

The Environmental Impact has been computed using the EIME software. Its presentation can be found in ref. [4]. We considered only the making phase.
We compared the 3000mm² bare copper cable with the 2500mm² enamelled one.



The making of the enamelled cable has globally a lower impact on the environment than the bare copper one. This effect is even more pronounced when taking into account the installation and civil works (smaller cable diameter, longer delivery length). The only drawback at the manufacturing stage regards the hazardous waste production. Although this waste production is very limited. Studies are in progress to reduce it even further.

CONCLUSION

By using improved Milliken conductors with insulated wires gains are achieved in almost all technical and economical aspects of power UG cable transmission:
For a given requirement in terms of current carrying capacity (i.e. transmitted power), we obtain:

- Smaller cable
- Lighter cable
- Higher current carrying capacity
- Lower losses
- Same or better overload capacity
- Lower cost
- Reduced Environmental Impact

Enamelled conductor connection need special techniques but this is widely compensated by the saving in cable price and number of joints.
This new technology has been long term tested, type tested and implemented for a 2500 mm² XLPE 400 kV cable project in Abu Dhabi including 12.7 km of circuit.
Because of a high power demand (1000MVA per 3-phase circuit) and a very tough environment (40°C soil temperature) this project would not have been possible without this new technology.

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GLOSSARY

Ampacity: Neologism for current carrying capacity.
UG: Under ground