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PRACTICAL CONCLUSIONS FROM FIELD TRIALS OF A SUPERCONDUCTING CABLE

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Summary

Field trials of a Fully Flexible Superconducting Cable (60 kV/1000 A, design Klaudy-Kabelmetal) including the necessary potheads were performed successfully in a real grid for the first time in the world during the years 1977-1980 at Arnstein (Austria). The cable met all electrotechnical and cryotechnical field and test conditions.

Encouraged by this success and based on the experiences gained in Arnstein as well as on further theoretical and practical investigations, the authors propose a simplified version of the Fully Flexible Arnstein cable with an improved new superinsulation saving the nitrogen cooling stage.

The proposed cable is based on the corrugated tube principle (Wellmantel-technique of Kabelmetal) and offers an economically competitive and technically superior construction compared to presently favoured watercooled cables in the power range of 1 GW or even lower. This power rating is of interest already today for the electricity supply in densely populated areas and industrial centers.

Fully Flexible Superconducting Cables have the following essential advantages over other superconducting and conventional cables:
1. The cable can be fabricated in great lengths (a couple of hundred meters) at low cost with well proven methods and equipment.
2. They can be reeled, shipped, and laid like any conventional cable in individual sections.
3. They require no sophisticated expansion elements as the thermal length changes occuring during cooling cycles of the cables are compensated for thanks the elasticity of the corrugated tubes.
4. They guarantee high operational safety since only a small number of splices and joints are necessary for connecting the individual sections of the cables.
5. They offer a high lifetime compared to conventional cables.
6. They are especially suited for the transmission of base load power at power ratings down to 1 GW and at voltages of 100 - 140 kV.
7. Being superconducting cables, they offer the possibility of perfect electromagnetic shielding towards their environment. Shield currents cause practically no losses.
8. The cables require surprisingly small trench widths - an advantage which can not be achieved with any type of normal conducting cables.

Consequently Fully Flexible Superconducting Cables of the corrugated tube design will be of importance in connection with electrical high power transmission in future.

Introduction

Up to the early seventies the general opinion prevailed that the steady growth of energy consumption (doubling within every 10 years) observed up to that time, would continue at the same rate. Therefore, it seemed to be necessary to plan and build continuously additional electricity supply facilities of adequate power. Serious difficulties arose at the planning of transmission lines from the power plants to the consumers centers. A sufficient power increase of conventional high voltage overhead lines by increasing voltages above about 1 MV could not be considered anymore because of the then necessary large line poles and trench widths leading to defacement of landscape, interference with air traffic and property rights, and also because of corona disturbances. Consequently, extensive studies were made since the middle of the sixties in the USA, Europe, and Soviet Union to develop adequate underground high power transmission facilities. Mainly the following alternatives were considered: water-cooled, SF6-insulated, cryoresistive and superconducting cables.[1] The latter were considered to be economically competitive by most of the experts at power ratings above 3 GW.[2]

However, in the middle of the seventies a far reaching change of mind occured due to the oil crisis, the requests for environment protection, and a general unease with unlimited technical progress. Consequently the growth rate of the energy consumption dropped essentially and affected the planning of high power transmission lines drastically. Power levels much above 1 GW were no more to be expected before about the year 2000. Experts not aware of the work going on at Graz, where Fully Flexible Superconducting Cables were developed - and later on one such cable was tested under real field conditions[3] (Fig. 1) - advocated the opinion that work on superconducting cables should be postponed. Consequently in Europe research efforts in the power range up to 1 GW were concentrated mainly on the development of watercooled cables. Of the different types of watercooled cables (indirectly and directly cooled), especially cables with internal watercooling appeared to be of interest for the supply of densely populated areas, presently supplied with 100 - 140 kV distribution voltage.

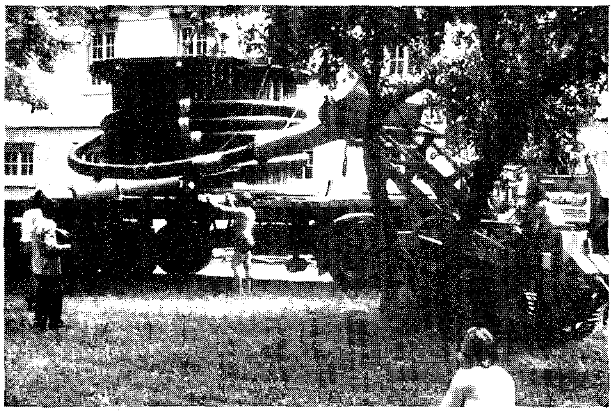

Fig. 1. Reeling off of the 50 m Fully Flexible Superconducting Cable for 60 kV/1000 A at the Arnstein power station.

Water-cooled Cables

Principally it may be said that water-cooled cables offer good efficiency under full load as well as under partial load conditions and temporarily can carry overloads due to their large heat capacity. At a first

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glance they also seem to be very simple. But, especially as far as internally cooled cables are concerned[4] (see Fig. 2), they turn out to be surprisingly sophisticated, as the following requirements must be fulfilled for their satisfactory performance: Provision of conductors with cross-sections of a couple of thousands of mm^2 subdivided into a number of profiled wires in order to ensure low losses and sufficient flexibility; de-ionization of the cooling water; absolute tightness of the water ducts in view of the very high water pressure necessary; allowance for changes of the cable length occuring at load variations causing temperature changes in the range from 30° C to 80° C; limitation of mechanical and chemical aging of the metallic parts as well as of the insulation; limitation of losses within the cable jackets by means of cross-bonding; a wide trench width for limitation of eddy currents within neighbouring metallic parts and for reduction of interference with adjacent communication lines. For all these reasons water-cooled cables do not represent the most suitable solution in all cases.

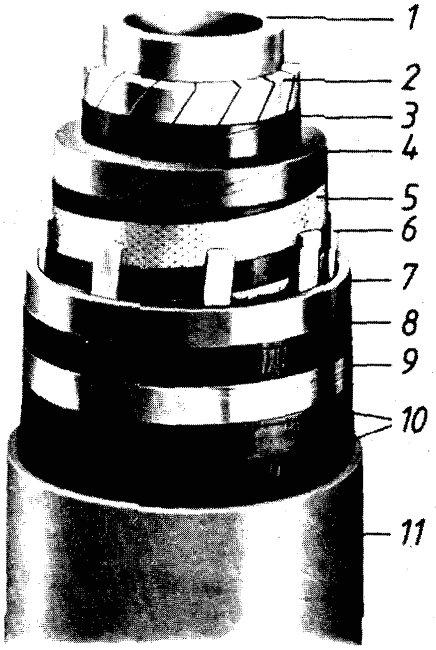

Fig. 2. Internally water-cooled Cable. 1-Cooling water duct 2-Aluminium profiled wires 3-Smoothing compound 4-Oil-impregnated paper tape insulation 5-Screen 6-Spacer 7-Lead jacket 8-Stuffing 9-Pressure band 10-Anticorrosion layer 11-PVC sheath

Fully Flexible AC Superconducting Cables

Contrary to some other institutions, where development work on superconducting cables has been discontinued at the end of the seventies, research at Graz has been carried on, aiming especially to develop superconducting AC cables competitive to water-cooled cables in the power range of about 1 GW which is of interest already presently. Analysis of all kinds of known superconducting cables, which had been proposed until the middle of the seventies convinced us that only Fully Flexible Cables similar to the one suggested by one of the authors (Klaudy) already in 1965,[1] could be made and operated economically competitive to water-cooled cables. The reason is that only cables of this flexible type would meet the following fundamental requirements:
simple and robust construction; low production cost by means of well proven process; possibility to produce long individual sections suitable to reel, to transport, and to lay them out at the site similarly to conventional cables; small number of cable joints resulting in a high operational safety.

In order to investigate whether these objectives actually are achievable, a Fully Flexible Superconducting Cable for 60 kV/1000 A, consisting almost entirely of corrugated metallic tubes, was built as a first step (Fig. 3).[5] It was installed in the grid of the public utility company STEWEAG in Austria, adjacent to the power station Arnstein (Fig. 4).

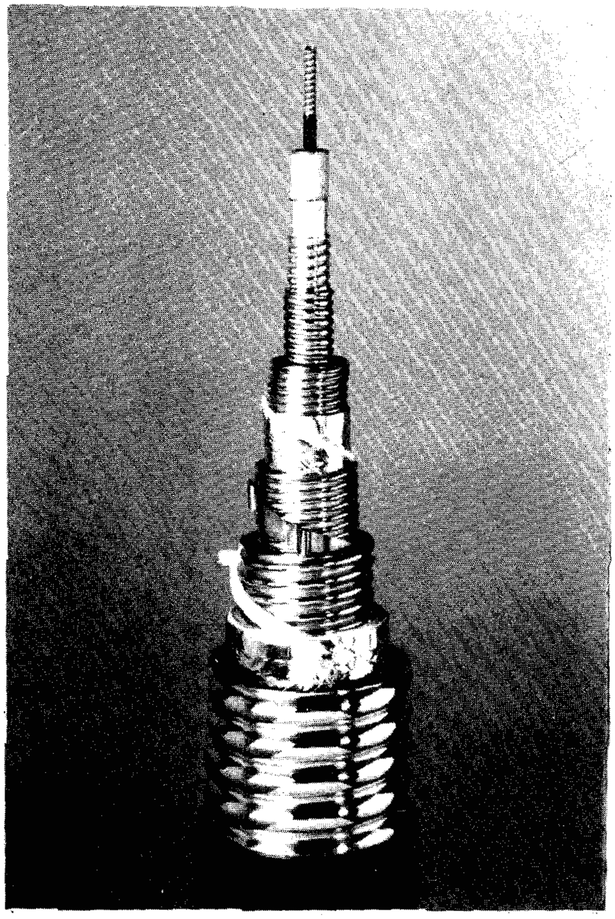

Fig. 3. Fully Flexible AC Superconducting Cable

At the end of 1979 and during 1980 this cable was tested as the first superconducting cable in the world under real field conditions, and showd fully satisfactory performance.[6]

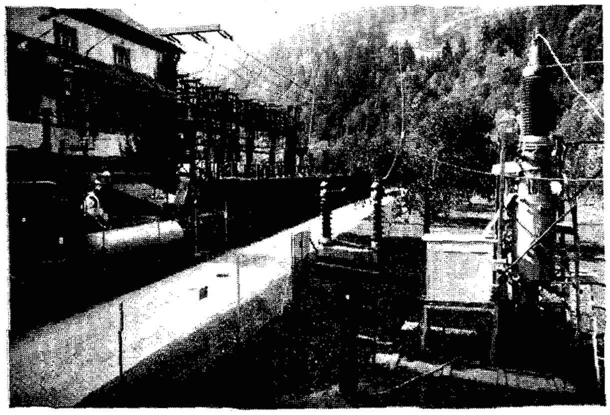

Fig. 4. 60 kV Cable-test facility at Arnstein

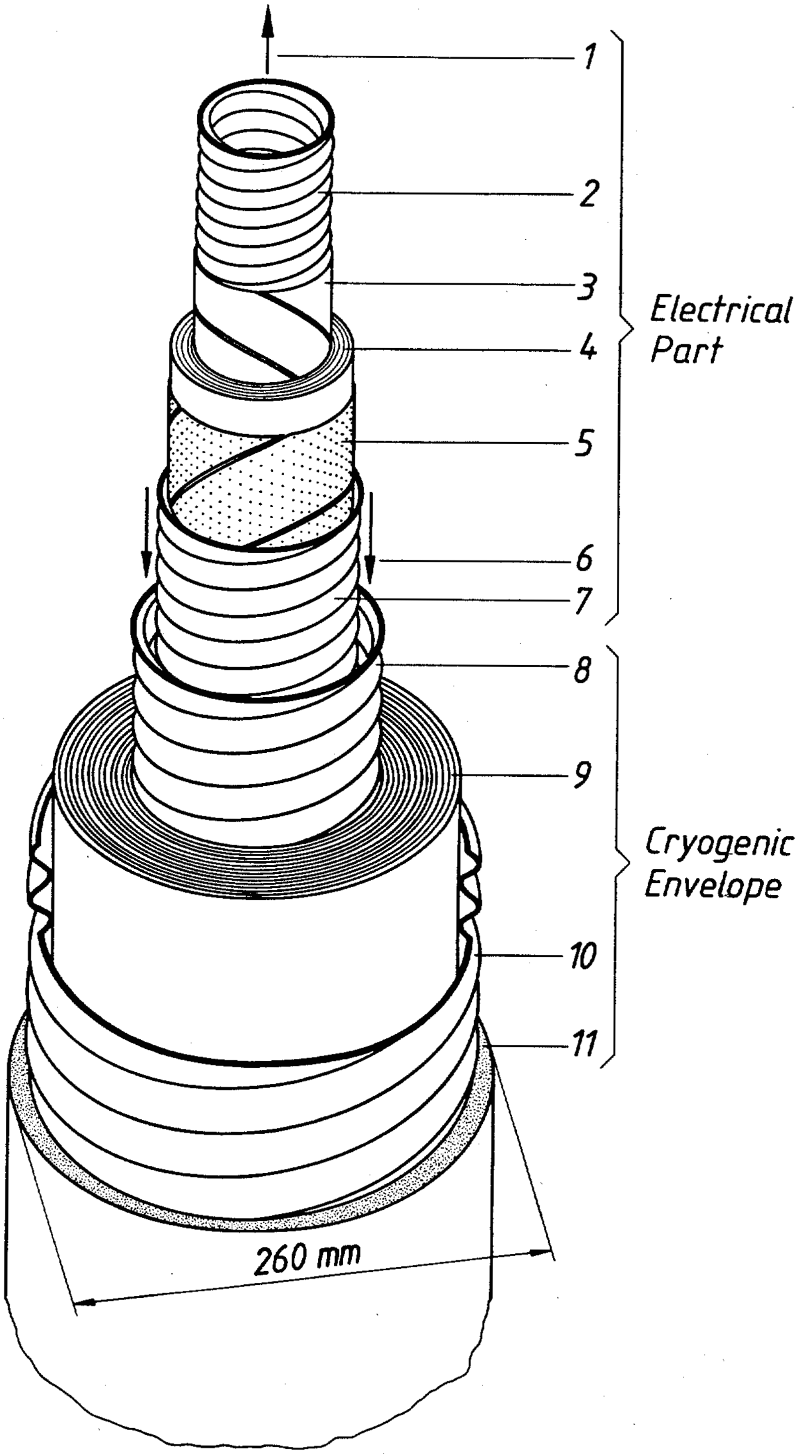

Fig. 5. Fully Flexible Superconducting Cable for 1/3 GW / 110 kV (Design Klaudy-Kabelmetal). 1-Cooling helium 2-Corrugated copper tube with superconducting niobium layer as the phase conductor 3-Smoothing compound 4-Helium impregnated paper tape insulation 5-Electrostatic screen 6-Cooling helium 7-Corrugated copper tube with niobium layer as the shield conductor 8-Inner corrugated tube of the cryogenic envelope 9-Superinsulation in vacuum 10-Outer corrugated tube of the cryogenic envelope 11-PVC-sheath.

Main Data and Conclusions from the Arnstein Trials

The cable was fabricated in a single section of 50 m length, shipped and laid out like a conventional cable in Arnstein (see Fig. 1).[3] During the tests cooldown and warmup to normal temperature was performed five times without damage thanks to the elasticity of the corrugated tubes. The cooling process to 6.3 K could be controlled easily even though two helium refrigerators were used in the system. The reason for using two refrigerators was an unexpected heat leak into auxiliary lines. Only one technician was needed to supervise the whole cable test facility around the clock. No partial discharges were observed during normal service (38 kV line to ground voltage) within the cable insulation. Flashover occured only at one terminal at a test voltage above 135 kV. Current tests carried out at low voltage and currents up to 1000 A showed satisfactory performance of the phase conductor and the shield conductor.[3]

The tests demonstrated that superconducting cables principally can be used under the rough conditions prevailing in actual power grids. It is for this reason that on the basis of the gathered experiences and further theoretical considerations an improved and simplified flexible superconducting cable for 1 GW/110 kV is proposed.

Fully Flexible Superconducting Cable for 1 GW/110 kV

In order to achieve most economical manufacture, transportation, and laying out of the cable on the site, three single-phase cables of 1/3 GW instead of one three-phase cable for the full power rating were taken into consideration for the transmission system. Each individual single-phase cable consists of four concentric corrugated tubes, see Fig. 5. The two inner tubes carry the phase conductor and the concentric so called shield conductor; together with the paper tape insulation in between they form the "electrical part" of the cable.

The evacuated space between the two outer tubes is filled with a newly developed superinsulation and serves as a shield preventing heat entering from the outside into the cable (cryogenic envelope).

Electric part. The phase conductor consists of a less than 100 μ thick niobium layer which is superconducting during normal normal operation ($T = 6.5$ K; $H = 3\cdot10^4$ A/m). At this magnetic field strength the AC losses in the superconductor are negligible.[6] The current flows actually only on the surface of the niobium layer of less than 0.1 μ thickness with an extremely high current density. The Nb-layer is deposited on the outside of the innermost currugated copper tube (see Fig. 5) of 60 mm outer diameter by a special process developed by Kabelmetal.[3] The small AC losses arising in the superconducting layer and about half of the dielectric losses in the surrounding helium impregnated paper tape insulation are removed by supercritical cooling helium circulating through the copper tube with a pressure of about 0.5 MPa. When a short circuit arises, the niobium layer is quenched, and the current is taken over by the copper tube until the short circuit is shut off by the power switch (stabilisation).

The 10 mm thick electric insulation consists of paper tapes-similar to that in conventional cables. It is impregnated with supercritical helium at a pressure of 1 MPa in order to achieve high dielectric strength.[7] No helium flow through the insulation is provided during normal operation in order to avoid the danger of impairing the dielectric strength by dragging along small foreign particles. Due to the low permittivity ($\varepsilon_r \sim 1.7$) of this insulation, which needs no dehydration before impregnation as water molecules will be frozen, the capacitance of the cable will be only 0.33 nF/m; dielectric losses will amount to about 0.15 W/m at 6.5 K.[8]

For the purpose of electromagnetic shielding toward the outside, the insulation again is surrounded concentrically by a grounded corrugated copper tube of 92 mm outer diameter carrying a thin superconducting Nb-layer on its inner surface. The insignificant AC losses in this shield conductor and about the other half of the dielectric losses in the insulation are removed by supercritical cooling helium which circulates around the outer surface of the shield conductor.

The dimensions of the phase conductor and the shield conductor respectively have been chosen considering maximal power density for the cable which is obtained theoretically at a diameter ratio of $\sqrt{e}$.

Cryogenic envelope. As has been mentioned already, the purpose of the cryogenic envelope is to minimize the heat entering from the outside into the cable. This heat is independent of the actual load conditions of the cable and is to be removed by the cooling helium circulating around the shield conductor. An intermediate LN2-cooling stage as it still was used in the Arnstein cable is not provided to ensure operational simplicity, and in order to lower manufacturing cost. The cryogenic envelope itself consists of only two concentric corrugated tubes (see Fig. 5), surrounding the electrical part of the cable. The evacuated space between these tubes is filled with a new improved superinsulation.

The omittance of the nitrogen cooling stage is justified by the application of the new superinsulation (see Fig. 6) which serves both as a spacer and as a heat radiation shield. It fills the evacuated annular space of the cryogenic envelope between its inner corrugated stainless steel tube and its outer corrugated tube, which is either formed of steel, copper, or aluminium, or eventually of a flexible nonmetallic material.

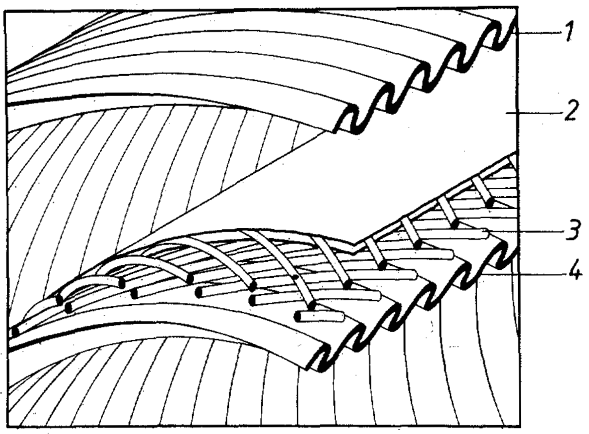

Fig. 6. Superinsulation. 1-Outer corrugated tube of the cryogenic envelope 2-Heat reflecting foil 3-Lattice strings 4-Inner corrugated tube of the cryogenic envelope.

The proposed superinsulation can be wrapped completely automatically. It consists of several latticed layers with intermediary heat reflecting foils, see Fig. 6. The elastic lattice strings of low heat conductivity touch each other only at the crossing points in very small contact areas (Hertz areas) where they take up the forces (up to 15000 N/m) occuring between the corrugated tubes during bending of the cable. Thus conventional spacers between both corrugated tubes can be omitted.

According to the results of preliminary tests, it can be expected that in the worst case the heat influx into the inner tube (with a temperature of 6.5 K) can be limited to less than 0.8 W/m when this superinsulation is applied. By using an improved refrigerator cycle as proposed by BNL,[9] an overall efficiency of the Fully Flexible Superconducting Cable can be expected which is comparable to that of internally water-cooled cables under full load conditions.

Advantages of the proposed cable. The described homogeneous corrugated tube system has the following advantages: all contractions and expansions during cooldown and warm up of the cable respectively are compensated for by the elasticity of the corrugated tubes without the necessity of providing complicated extension elements.

It is of special importance that the electric part of the cable and the cryogenic envelope can be manufactured and completely tested in the factory by means of proven methods and equipment. Furthermore they can be reeled separately in adequate section length and transported to the site like ordinary cables. On the site the evacuated and sealed sections (not more than about 250 m for the reason of easy evacuation) of the cryogenic envelope will first be laid out and then joined by simple cryogenic connections. Thereupon the electric part consisting of single lengths of about 750 - 1000 m is pulled into the laid out and joined cryogenic envelopes (see Fig. 7). In such a way the number of electrical splices can be kept small resulting in a high safety in operation.

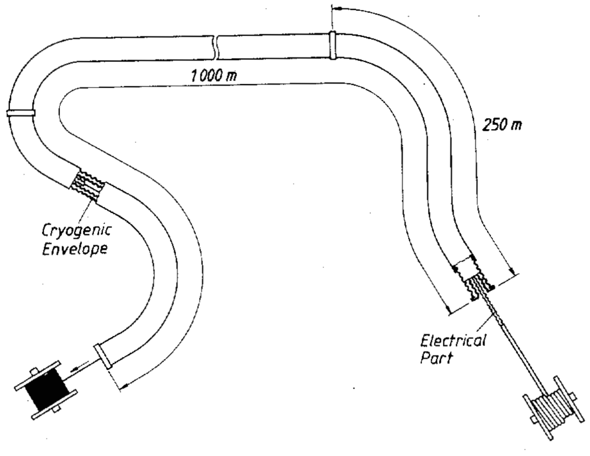

Fig. 7. Laying out of Fully Flexible Superconducting Cables.

The lifetime of superconducting cables can be considered higher than that one of water-cooled cables since mechanical and chemical aging of the materials used are minimized thanks to the constant operational temperature near absolute zero.

Since only superconducting cables offer the possibility of practically lossles current flow in the shield conductors, a circuit arrangement as shown in Fig. 8 can be recommended. The ends of the three phases of the power source (transformer or possibly a high voltage generator with superconducting exciting coils) are connected to the corresponding shield conductors in the cable, and these again are joined at the cable end to the neutral point.[10]

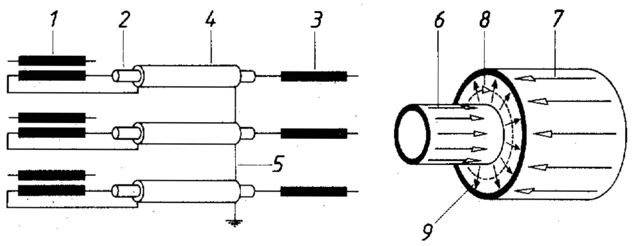

Fig. 8. Three-phase Circuit arrangement. 1-Power source 2-Phase conductor of the cable 3-Load 4-Shield conductor of the cable 5-Neutral point 6-Phase current 7-Shield current 8-Magnetic flux lines 9-Electrical field lines.

Thereby any electromagnetic interference with the environment is avoided. Since the three single-phase cables cannot influence each other, Their spatial arrangement can be chosen in accordance with any particular local requirement. The necessary trench width is merely determined by the space the cables themselves occupy. A particularly favourable arrangement is shown in Fig. 9. Water-cooled cables, on the other hand, require a much larger trench width due to the interferences of strong electromagnetic stray fields with the surroundings.

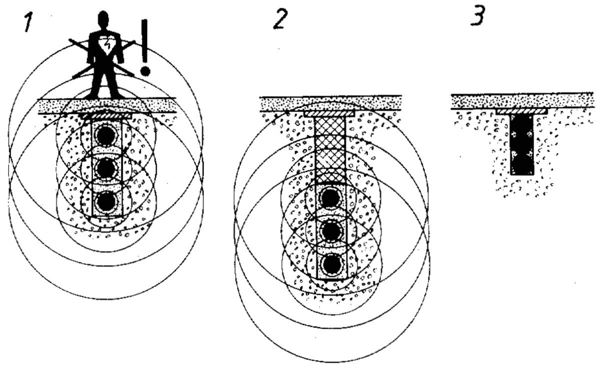

Fig. 9. Spatial requirements of high power transmission cable. 1-Water-cooled cable with dangerous stray fields 2-Water-cooled cable properly arranged 3-Superconducting cable without stray fields.

Economic Considerations. The proposed Fully Flexible Superconducting Cable type appears especially suitable for the power supply of 110 kV distribution grids in densely populated areas and industrial centers, where cable lengths between a few up to 20 km come into consideration.

Therfore, cost estimates for a 10 km long cable were made resulting in a total figure (including potheads, cryogenic joints, splices, laying work, property rights, and cooling stations) of about US $ 21 millions. For a greater number or greater lengths of such cables a corresponding reduction of cost per unit length can be expected.

For comparison, the cost of a high voltage indirectly water-cooled cable - being a conventionally constructed oil cable of 12 km length and presently under field tests in Vienna - amounts to US $ 31 millions.

For an internally directly water-cooled cable of 10 km length and the same power at 110 kV, even higher costs will be encountered.

Future improvements. The technical and economical advantages of the described Fully Flexible Superconducting Cable will still be enhanced when - as can be expected - further improvements in the production of superconducting materials with higher critical temperatures (for instance Nb3Sn, Nb3Ge) will be achieved, as higher temperatures within the cable lead to more economic cooling systems. Furthermore, newly developed electrical insulation materials may be used.

It is therefore to be expected that Fully Flexible Superconducting Cables of the described corrugated tube design (Klaudy-Kabelmetal) will be of considerable importance for the future power transmission in special cases.

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