

Designs and Applications of HTS

Continuously Transposed Cable

N.J. Long
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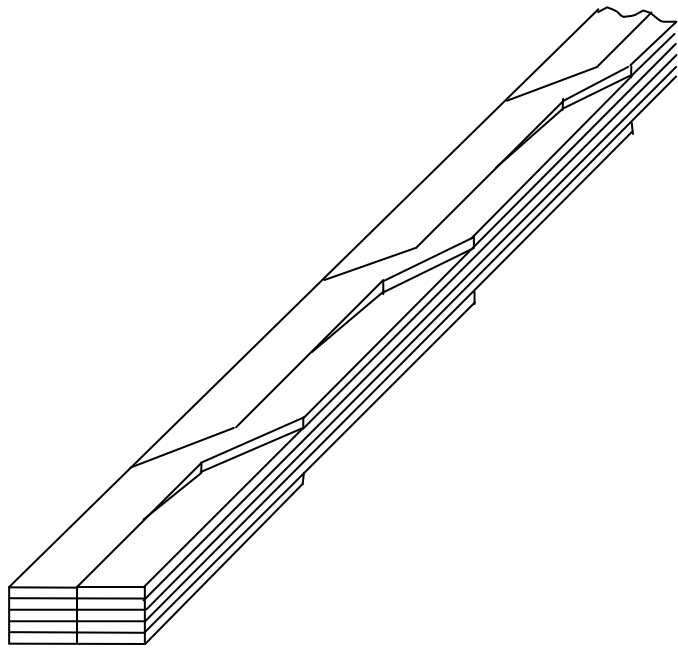


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Executive summary

Rapid progress is being made in the commercialisation of second generation (2G) HTS wire for DC applications. Although some concepts to lower AC loss for AC applications such as filamentization have been suggested many of the proposed architectures are difficult to implement, require further twisting when incorporated in a device, or do not fully address issues such as stabilisation. We propose the development of a continuously transposed cable (CTC) using 2G wire which looks very similar to conventional copper CTC's. Such a cable has been developed using the 1G conductor but there has been little consideration among researchers of using 2G HTS.

We propose several different architectures for a 2G CTC which have benefits both for AC and DC applications. Calculating the exact AC loss in a CTC is beyond this review as it requires detailed modelling and greater knowledge of specific application designs than we have at present. It also depends on the final filament width achievable, at present we believe this will be in the range of 1-2mm. However, using general considerations from previous AC loss studies, we argue that the cable can reduce AC loss in applications such as transformers and induction heaters into the range where they become seriously viable technologies.

Introduction

Continuously transposed cables or conductors (CTC) were invented by Ludwig Roebel in 1911 to minimise circulating current losses in the windings of electrical machines such as generators and transformers. The conductors are commonly called Roebel bars when used in generator stators. Innovations in Roebel conductors, particularly in the material components, continue to be made almost 100 years after Roebel's breakthrough.

Figure 1 illustrates a CTC consisting of a group of rectangular wires, arranged in two stacks. In this group each wire is transposed in turn without twist along its length. It can be seen that each wire successively and repeatedly takes on every possible position inside the whole conductor cross-section. This arrangement cleverly reduces eddy currents in the conductor arising from external or self generated AC fields. The individual conductor strands have a width W , and a thickness d . The length P , is the

“transposing pitch” over which the cable repeats its configuration. The length over which an individual strand returns to its original position is equal to the number of conductors times the transposing pitch and is called the “stranding pitch” or “transposing lay”.

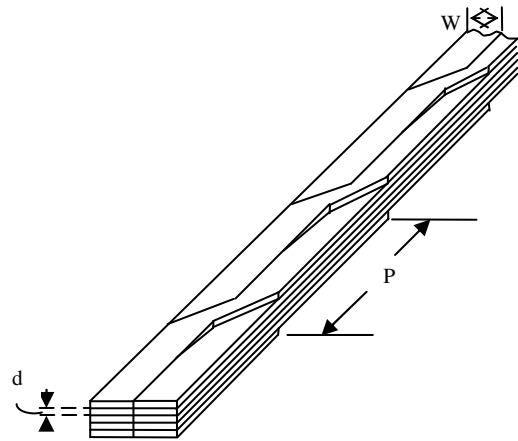


Figure 1: A ten strand CTC

Conventional Roebel bars usually contain an even number of strands, but may also be made from odd numbers, with the added benefit of increasing the conductor cross section by one strip within the same stack size. Numbers of strands typically range from 5 to about 60. Paper tapes are wrapped around the assembly as external insulation and this permits a large variation in the thickness and choice of insulation.

The use of CTC brings a number of advantages to electrical machine design which are directly applicable to superconducting machines.

- Reduction of AC losses
- Increase in mechanical strength of windings, particularly their ability to withstand the electrodynamic stresses caused by short circuiting
- Increase in the space factor of the winding due to the reduced insulation thickness
- Improved heat dissipation
- Reduced winding time for large coils
- Flexibility in architecture, e.g. transposing pitch and current capacity

The strongest driver for using a CTC in superconductor applications is reduced AC loss. This factor will be examined in detail in the following sections. However, other

drivers such as the above and the flexibility to create a conductor with very high I_c are of potential interest.

CTC design

Conventional CTC's

Copper CTC's are manufactured by a four step process which involves bending in the plane of the rectangular tape.

- Step 1 Conductor #1 is bent across from the top of the right hand stack to the top of the left hand
- Step 2 The right hand stack is moved up one conductor thickness in relation to the left hand stack.
- Step 3 Conductor #4 is bent across from the bottom of the left hand stack to the bottom of the right hand stack.
- Step 4 The left hand stack is moved down one conductor thickness in relation to the right hand stack.

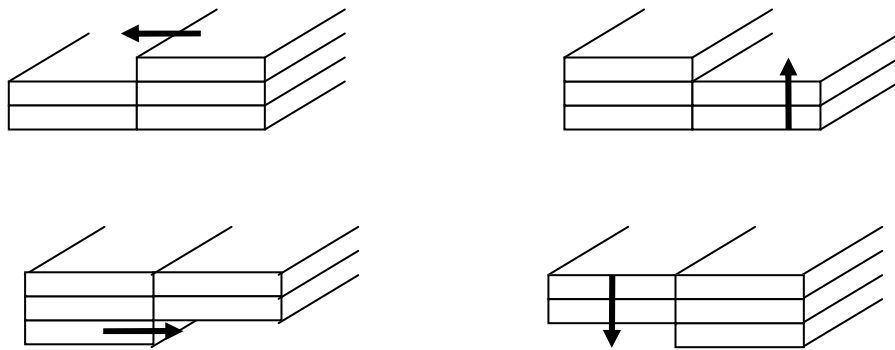


Figure 2: Assembly procedure for a copper CTC. The strand is anchored at some point and then bent into the new position.

Superconductor CTC's

This same process has been applied to BSCCO 1G wire by groups such as Siemens [Leghissa et al] who made a 13 strand CTC for use in the low voltage coils of a traction transformer. In the case of BSCCO great care has to be taken to control the radius of curvature of the bend or else the superconducting properties of the tape are greatly degraded.

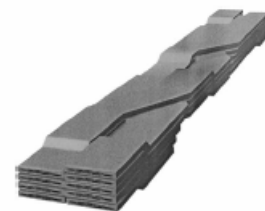


Figure 3: An illustration of the Siemens 1G cable

The second generation YBCO conductor is a thin film conductor with a large aspect ratio. For this reason edgewise bending of the tape has generally not been considered feasible for producing a CTC. Other AC loss reduction strategies such as filamentization have received much more attention [C.B Cobb et al]. An exception

has been the work of Suzuki et al [Suzuki et al] who have experimented with bending 2G wire and accepting the slop in the cable due to the inability to produce plastic deformation of the wire. In comparison with the solution described here this produces a conductor with reduced critical current density and difficult mechanical properties. The uneven profile of the conductor may also make it susceptible to damage.

We have invented an alternative method to produce a CTC using 2G wire. This involves manufacturing pre-cut strands in the general shape shown in Figure 4. The process to form the wire is then different from the process used for copper wire in that no deformation is necessary but rather the wire must be twisted into place. A manual assembly procedure for a 2G wire CTC is given in appendix A. Using mechanical cutting it is expected that strands with 2mm diameter can be made. We have received advice that 1mm strands should be possible using laser cutting, provided the laser power and frequency are well matched to the material, this has yet to be demonstrated.

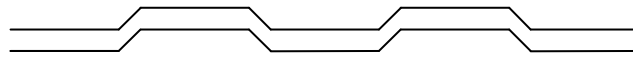


Figure 4: The general shape of a pre cut strand used to form a CTC

The primary design for the CTC requires that the individual strands are essentially isolated with only a small degree of current sharing to stabilise the conductor. However we also consider designs with greater degrees of current sharing which may be useful in DC or low frequency applications which require high currents and low inductance. For illustrative purposes we consider a five strand conductor but the principles generalise to any number of strands. In all cases it is expected that the individual strands would be soldered together in the final package. Insulation of the package would comprise wrapped layers of paper as for copper CTC's.

There are a number of possible architectures for the HTS wire itself which impact on the design of the CTC. The basic architecture is shown in figure 5. In addition the HTS wire requires extra stabilising conductor, usually copper, to provide a parallel current path bypassing any small faults in the HTS and providing good heat conduction to the cryo-system. By matching the copper thickness to the substrate thickness so called “neutral axis” wire is created in which the HTS layer is placed in the centre of the tape where the tensile and compressive bending strains are zero.

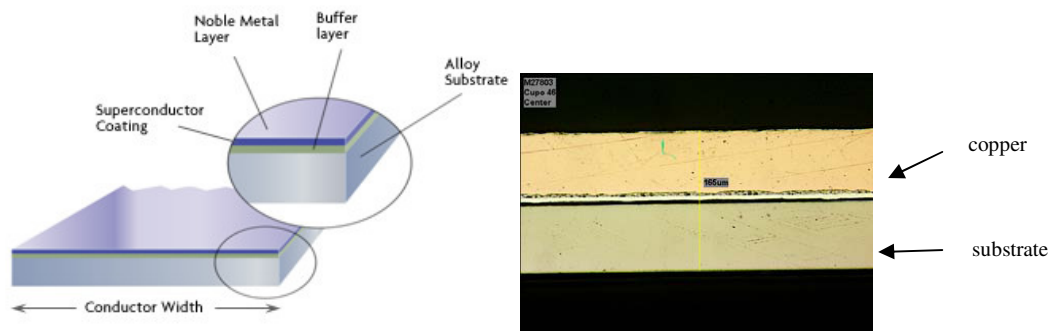


Figure 5: a) General architecture of 2G HTS wire before packaging. b) Micrograph of neutral axis wire. The substrate thickness is 50-75 microns.

In addition to neutral axis wire there are other possibilities for the wire architecture. One is to place two wires face to face with a stabilising layer between. The difficulty with this arrangement is that current is not easily injected into the composite wire. Another proposal has been to coat both sides of a substrate with superconductor. This has not been greatly pursued by researchers because of the difficulties of handling the tape during production and because the superconducting layers are not easily connected to improve stabilisation.

Four proposed CTC architectures

(1) Non-current sharing design

The asymmetry in the HTS packaging can be exploited in the CTC. For example if the desire is to minimise current sharing between the strands of the CTC then the tapes can be arranged as shown in Figure 6 (a). In this case there is never any face-to-face contact of conducting elements and any current sharing can only occur through edge contacts or through the substrate and (non-conducting) buffer layers. This design produces a CTC which is asymmetric with respect to current injection or removal and the CTC has a “top” and a “bottom” surface.

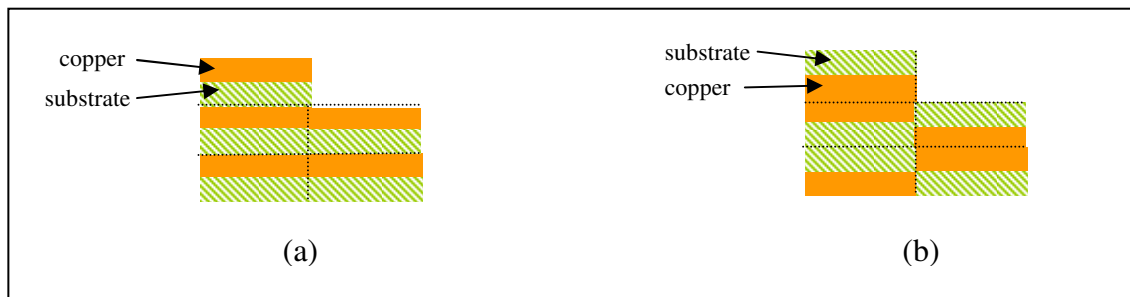


Figure 6: A cross section of a five strand CTC illustrating (a) non current sharing and (b) current sharing configurations.

(2) Current sharing design

In configuration (b) half the conductors have been turned upside down (actually for a conductor with $2n+1$ strands, either n or $n+1$ are reversed). Now two pairs of conductor have a high conductivity copper to copper connection. Further, as the strands are transposed all vertically adjacent conductors will at some point have a copper to copper contact, so a high conductivity path is available between all strands. For purposes of current injection and splicing the conductor is essentially symmetric. The degree of current sharing in this configuration can be controlled by adding a further partially conductive layer to the copper surface before assembly or by choosing a stabilising layer other than copper.

(3) High current density I

When the 2G wire has passed through the YBCO manufacturing process it generally has an oxide scale present on the substrate surface. One option for packaging the HTS is to remove the oxide scale and then electroplate the surface with copper. If this is possible then a high current density CTC which partially uses the Ni substrate as stabilisation is possible. The HTS wire as illustrated in Figure 7(a) can be arranged as in (b) to form the CTC. A further copper lamination could be added to the top and bottom of the CTC to provide extra stabilisation if needed. The orientation of the HTS strands and the thickness of the

copper electroplated layer could also be varied to optimise current density and stability.

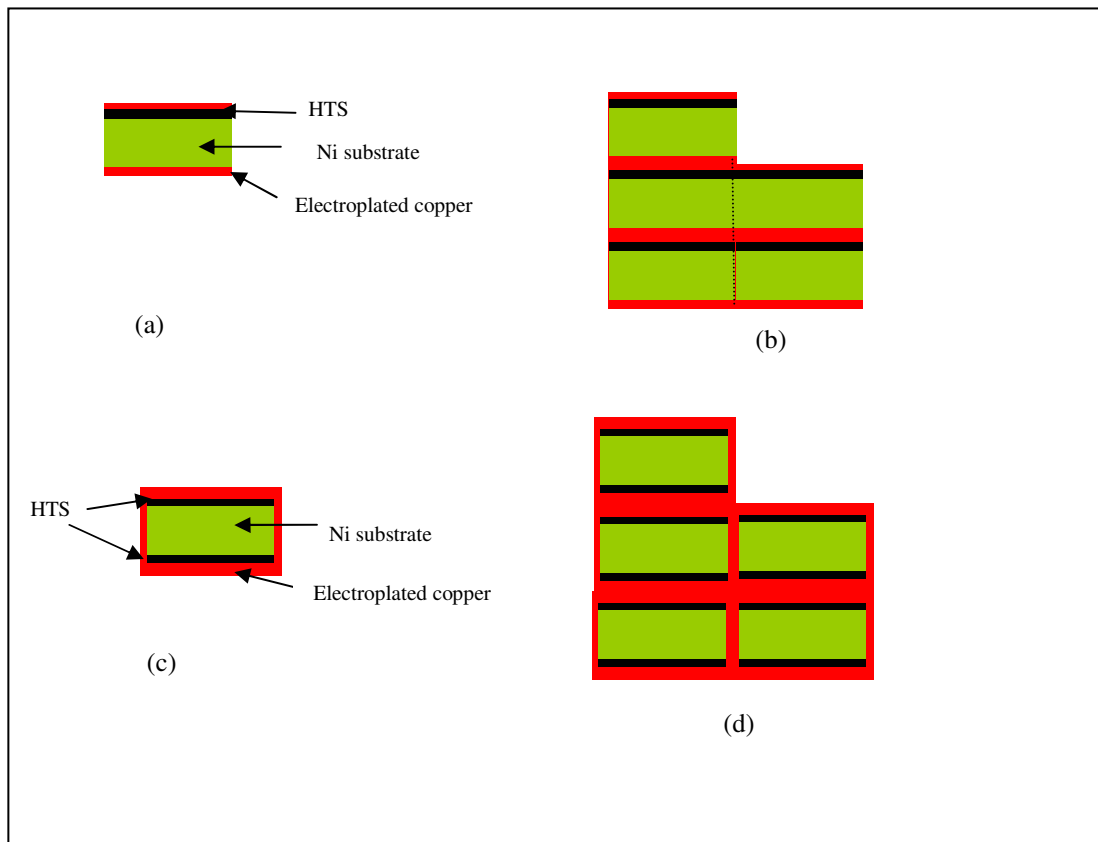


Figure 7: (a) HTS wire with electroplated copper packaging, (b) high current density I CTC (c) HTS wire with double sided coating, (d) high current density II CTC

(4) High current density II

A further possibility is to use strands with superconducting layers on both faces. Because the strands are naturally in a current sharing configuration this means that injecting and removing current is straightforward and can be done from either face of the cable. The use of stabilisation is also optimised in this configuration.

CTC piece length and strand splicing

Due to the complexities of the HTS wire manufacturing process discontinuities in I_c have proved inevitable and are likely to remain for the foreseeable future. This necessitates removing low I_c segments of wire and limits the continuous piece lengths available for application builders. Producing long piece lengths simplifies application manufacture and commands a price premium. The introduction of splices in the wire creates mechanical weaknesses which can cause problems, for example in rotating machinery.

The proposed CTC designs offer the possibility of making conductors with predetermined lengths in which splices can be incorporated without significant impact on either the electrical or mechanical properties. For example if the current sharing design is used then a new strand can be butted to the end of a broken strand. The unaffected strands within a distance of a stranding pitch will be required to carry extra current but only of the order of $1/N$, where N is the number of strands. For the non

current sharing design a splice in the strand would need to be introduced, however the impact on the total current capacity of the wire would be minimal. Likewise the change in the mechanical properties of the CTC due to a splice in 1/N strands is minimal.

We would foresee application developers being able to order CTC's to a predetermined length so that no splicing by the application builder is necessary. The incorporation of paper insulation also simplifies application building and the insulation can easily be removed for current lead attachment.

Defect tolerance and thermal stability

The arguments around strand splicing in the current sharing design are also applicable to the tolerance of small I_c dropouts in the conductor. A multiple strand conductor will be more tolerant of defects due to the low probability of having a coincidence of defects in different strands. This will make CTC's less likely to quench.

CTC splicing and current injection

Some proposed architectures for HTS packaging have foundered because splicing and/or current injection become problematic. Because we believe CTC's can be manufactured to a predetermined length splicing of CTC's themselves should rarely be necessary. We discuss current injection/removal and splicing for the three architectures we have proposed.

- (1) Non-current sharing design: current injection/removal is not difficult as over the stranding pitch all HTS layers are accessible from the top surface. As long as current leads are soldered with an overlap of one stranding pitch then there should not be a problem. Two cables can be spliced in the same manner by overlapping the top surfaces.
- (2) Current sharing design: Only half the HTS layers are directly accessible over a stranding pitch. However, as there is current sharing within the cable then provided a long enough overlap with the current leads is provided, current injection/removal shouldn't be problematic. Also having a split current lead contacting both top and bottom surfaces would solve the problem. Similarly with splicing, as the CTC is essentially symmetric, either top or bottom surfaces can be overlapped and joined. What constitutes a "long enough" overlap needs to be determined for a particular cable and application.
- (3) The high current density CTC is essentially the same as the non-current sharing design and can be contacted and spliced in the same way.

Mechanical properties of CTC

An advantage of copper CTC that applies equally to superconductors is their improved mechanical strength. The compressive and tensile strength of HTS wire has been an issue for developers of rotating machinery and the c -axis strength of 2G wire remains a potential stumbling block. Because in a superconductor CTC a number of strands will be soldered together the compressive and tensile strength will greatly exceed anything achievable by a single wire. The greater robustness of a CTC should reduce the likelihood of introducing wire defects during winding and improve yield in application manufacture.

The minimum bending radius of the CTC will depend on the number of strands and the packaging of the individual strands. All strands experience the same mechanical

stresses if the wire is bent uniformly and the strands will alternately be in compression and tension depending on where they are positioned within the cable.

Using a CTC may also help in applications requiring high c-axis strength. Partly this can be achieved by using narrower strands. The use of a high J_c design also allows greatly flexibility in the packaging without fatally compromising the overall current density.

AC loss of high temperature superconductors

Upper limit to acceptable AC loss

The units of AC loss which are most applicable to high current devices is W/Am – the energy loss per second, per ampere of current transported, per metre length of the windings. To calculate the power loss for an HTS device a cooling penalty factor, ϵ_c is introduced to account for the extra energy required to extract heat from low temperature. The length of the conductor in the device and the total current in the device are assumed to be fixed parameters. Therefore the relevant design parameter is the product $\epsilon_c P / I$, which should be minimised, where P is the power loss per meter in the conductor and I is the current in the conductor.

General upper limits on AC loss for HTS can be derived from comparison with the losses in copper based devices and allowing for the cooling penalty factor. For copper operated at a typical value of $2A/mm^2$ without forced cooling the power loss $\epsilon_c P / I$ is 15mW/Am for a sine-wave current [M. Oomen]. Assuming a cooling penalty of 15 for operation at liquid nitrogen temperature the total power consumption p_{dev} in the HTS device is equal to that in a copper device if P / I_c is 1.0mW/Am.

To justify the added complexity of a superconducting device normally the loss will need to be significantly lower than 1.0mW/Am. Target values for transformers for example, have been quoted as 0.2-0.8mW/Am [Marsh and Wolsky, Hornfelt, Leghissa et al, Nagasawa et al]. This may not be the case if size and weight of the device are the primary drivers for adopting HTS technology, e.g. for transportation applications. In this case a loss closer to 1.0mW/Am may be justifiable. For transformers there are also environmental advantages in the use of nitrogen as a coolant rather than oil. Transformers and fault current limiters may also bring network advantages which justify the added complexity.

AC loss in HTS materials

A detailed model to calculate the AC loss in a device is well beyond the scope of this review. Neither will we attempt a comprehensive literature review. The goal is to use some very rough approximations to estimate the usefulness of the CTC in meeting targets for AC loss.

There are a number of loss mechanisms which are active in the conductor depending on the local magnetic field, frequency and current conditions. The ferromagnetic substrate will contribute a small hysteresis loss although this has shown to be negligible under most conditions and we will ignore it [Ijaduola et al]. There are also eddy current losses in metal components although at the frequencies of the devices we consider these will not be significant. The loss which can be considered to be

dominant in the devices we consider is the magnetisation loss without transport current. For an applied magnetic field B_a and frequency f , the loss is

$$P / I_c = B_a f d_x$$

where d_x is the largest dimension perpendicular to the field, P is the power loss per meter and I_c is the critical current. We assume that the field is large enough to fully penetrate the superconductor.

Following Oomen [M.P. Oomen] we can use this to estimate the AC loss for 1G and 2G wires in various applications (see table 1).

Table 1: Approximate AC loss in power devices

Property [unit]	Transmission cable	Transformer	Motor or generator, AC winding
Frequency of the field f , [Hz]	50	50	20
Field amplitude $B_{a,\parallel}$ parallel to the tape [T]	0.01	0.1	1
Field amplitude $B_{a,\perp}$ perpendicular to the tape [T]	-	0.01	1
1G wire 4*0.2mm ²	P/I_c due to $B_{a,\parallel}$ [mW/Am]	0.1	4
	P/I_c due to $B_{z,\perp}$ [mW/Am]	-	80
2G wire, 4*0.002mm ²	P/I_c due to $B_{a,\parallel}$ [mW/Am]	0.001	0.04
	P/I_c due to $B_{z,\perp}$ [mW/Am]	-	80

Specific Applications

Transmission cables

The magnetic field in transmission cables is weak and therefore the AC loss is well within budget even for 1G wire. The use of 2G wire will improve things further. The advantages of using a CTC therefore are likely to be in aspects other than AC loss. Possible advantages are:

- Simplified winding of the cable using a high I_c CTC.
- CTC's available to cable manufacturers in predetermined piece lengths – no splicing necessary.
- Improved current sharing using the current sharing CTC design
- Easier current injection/coupling to ends of cable
- Improved thermal stability
- Reduced space of the winding using a high current density design
- Possibility of using a straight stack rather than a wound cable.

Utility Transformers

In the low voltage windings of transformers the currents are in the kA range. To use HTS it is therefore necessary to use either a CTC winding or multiple in hand windings of the coils. A CTC has the advantage of reducing the complexity of the winding process and ensures good current sharing between the strands.

At the nominal goal of 0.25mW/Am for an HTS conductor the coil losses in a 10-MVA transformer would be 5% of today's losses in copper [i.e. (15x0.25 mW/Am)/(80mW/Am)] [Marsh and Wolsky]. The AC losses in a 1G transformer

prototype have been reported as 3mW/Am [Hornfelt] and correspond well to predicted values. Assuming the same design using a 4mm wide 2G wire would give losses of 2mW/Am. The use of a CTC with 2mm strands would bring the loss down to the magical number of 1mW/Am where HTS becomes attractive. If the loss could be reduced further either through improved overall design or reducing the strand width below 2mm then commercial HTS utility transformers may become a reality.

Traction transformers

Siemens have an active programme developing transformers for trains. They have developed a 13 strand CTC using 2mm diameter 1G tape. In transportation the reduction in size and weight is a primary driver so that slightly higher losses can be tolerated compared to other applications. It would be expected that a 2G CTC with a strand width of 2mm would have about 50% lower losses than the 1G cable. The 2G CTC would clearly supplant the 1G product if this market develops.

Induction heaters

Induction heaters are used to heat billets of metal before extrusion or other forming processes, for example aluminium billets are heated to around 500°C pre extrusion. The heaters work by inducing eddy currents in the metal. Conventional induction heaters are only about 55-60 per cent efficient when heating high conductivity materials such as copper and aluminium. The losses in the copper windings are around 400mW/Am.

A prototype heater using 1G wire has been made by SINTEF energy research. The current 1G wires give losses in the 15 to 20mW/Am range (x15 or 225-400mW/Am including the cooling penalty at 77K) if used in a 1MW class induction heater. The system would be viable if losses could be reduced to 10% or 100kW for a 1MW system. The target for HTS wire therefore is about 5mW/Am to make this technology viable.

The benefit of a 2G CTC can be estimated if we make the assumption that the ratio of parallel to perpendicular field losses is similar to those for a transformer, i.e. 1:2 for 1G wire. For parallel field components the use of 2G wire will likely reduce the losses to near zero. If we use a 2mm strand width rather than the 4mm then the losses in perpendicular field are reduced by half. Therefore a CTC with a 2mm strand width will reduce the loss from 15mW/Am to 5mW/Am making this a viable HTS technology.

Magnets

The generic benefits of using CTC such as increased effective J_e values due to the smaller fill factor of insulation and higher current density design may be valuable for applications where size and weight are important.

For NMR insert magnets the benefits would be particularly attractive:

- High strength
- Low inductance
- High current density
- Lower AC loss

Generators and motors

The mechanical properties of a CTC may make it useful within generators. The cable is better able to withstand the very high electrodynamic forces which may arise during a short circuit. Simplifying the winding process and decreasing the space of the windings may also be major advantages. AC losses are not a problem where HTS is used in the DC field coils of a rotating machine. The use of HTS in armature coils would require orders of magnitude reduction in AC loss and is not considered feasible by the use of a CTC as we have described.

Fault current limiters

Using the CTC concept allows a coil to be constructed with an I_c (A/cm-W) much larger than that for a single HTS wire. This also allows the inductance of the coil to be easily engineered. This flexibility may be of value in designing practical fault current limiters. The CTC cable also has greatly enhanced mechanical strength which will be of value in maintaining the integrity of the device under fault conditions.

SMES

The development of CTC will allow greater flexibility in SMES design to accommodate higher currents and lower inductance coils. Time dependent fields are present as the SMES charges and discharges however it is not clear that these will be the dominant losses in the system.

Summary

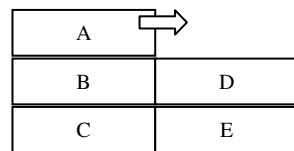
There are possible benefits to almost all devices in using CTC. The most attractive application is transformers as CTC has a natural use in the high current – low voltage coils. CTC is also a feasible strategy for reducing the AC loss in a transformer into the range where the technology is viable. Transformers are a large market using substantial quantities of conductor. The potential gains should easily justify the development costs for a CTC.

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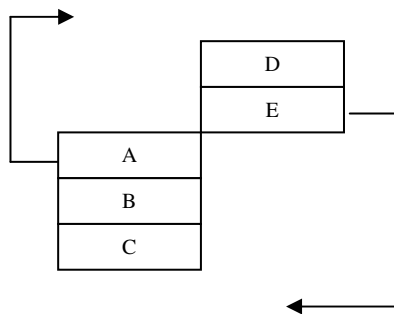
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Appendix A: Manual Assembly Process for a CTC

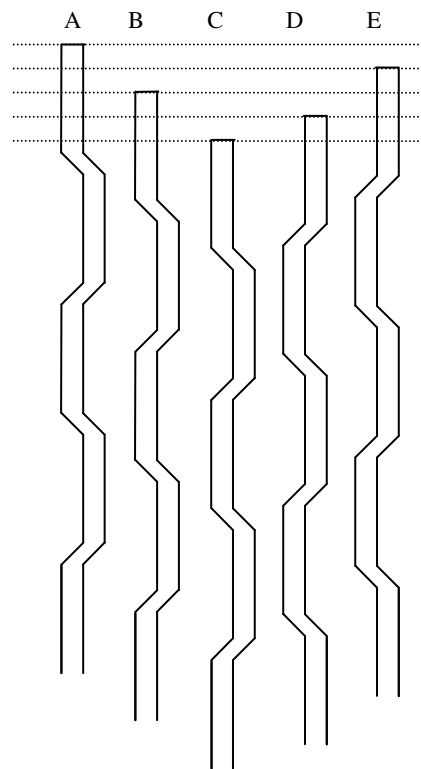
For illustration we will describe forming a 5 strand CTC using 2G wire. Imagine that the starting point is the cross section of the CTC as shown below in (a). The first transition is for strand “A” to move from left to right. The next transition will be for “E” to move from right to left. The strands must therefore be staggered before stacking as shown in (b). They are then stacked in the vertical order DEABC as shown in (c). The first transposition is then to “twist” tape A such that the cross over takes the tape above tape D. Tape E is then twisted so that its first cross over takes the tape under tape C. This process is then continued and can be summarised for an odd numbered stack by the 2 step algorithm: 1. Twist the middle tape of the stack to the left and to the top of the stack, 2. Twist the middle tape of the stack to the right and the bottom of the stack.



(a)



(c)



(b)