Glenn Auld Knierim, Ph.D.

Full Transposition Cable Core Fundamentals & Benefits

Technical Paper*

* The technical discussion herein presents qualitative concepts, supported by electrical and mechanical engineering principles. These concepts direct current and future application analyses and design studies.

Background

For manufactured electrical cables, circumferential winding configurations are by far the most common due to manufacturing ease. Systems using conventional conductors solve resistance loss by adding more cables or increased voltage. This causes increased power loss, cost, and right of ways to name a few issues. This leads to the need to install and operate more efficient power cables.

Inductance limits long length power transmission and cable-based magnet response more than any other factor. Increased inductance causes higher transient currents and magnetic fields resulting in issues such as limiting transient power transmission distance and increasing magnetic field interaction. To address inductance, a circumferential winding pattern involving full transposition is industry standard (see figure). This pattern is an evolution of a helical wind that simply wraps conductors around a core.

Full transposition (FT) is a technique of periodic position swapping and precisely placing conductors such that each conductor moves to share each position in a cable down the cable length. *FT commercial winding is required for long length AC cables, transient power, and AC, DC, and pulsed power in a high magnetic flux density (B) transient field.* As shown in the diagram below, depending upon operation FT cable cores lower ***reactance***, reduce ***AC losses***, improve ***reliability***, increase ***flexibility***, and improve ***quench protection***. FT lowers inductance thereby decreasing magnetic interaction between conductors arranged in an FT group, between FT groups in a cable, and between a cable and an external B. This effect is bi-directional such that effects are also mitigated from a B generated inside the cable to something sensitive outside. This allows a lower cost cable by reducing or removing costly cable external electromagnetic (EM) shielding layers. For **high B canceling operation**, a concentrated B across the cable core requires a higher number of FT period twists in the affected region to confirm that the external B effects are cancelled. In a **long cable**, even if the FT period length is too long to prevent localized interaction from a high B, the overall number of FT periods is extreme and hence the transposed positions will cancel any external magnetic effects. For **high B linking operation**, the FTs are arranged to superimpose rather than cancel the B. This level of design involves combining the cable core and final cable magnet designs.

Operation	FT Primary Benefits	FT Result
Transient	lowered reactance & AC losses	fast transient operation controlled transient operation long length AC operation
DC	improved reliability & bending	improved SC quench protection improved cable flexibility

Benefits of Full Transposition (FT) in Cable Cores

Fundamentals of Lowering Inductance by Using FT

Inductance is the property of an electric conductor or circuit that causes an electromotive force (emf) to be generated by a change in relative motion of a magnetic charge (or current). Lowering inductance lowers reactive power coupling which lowers associated emf response, current transient response lag times, and magnetic storage thereby lowering ***AC losses*** (including conventional conductor eddy current losses proportional to an increasing frequency^2), and for superconductors (SC), provides DC to transient FT ***quench protection*** (SC to SC, FT group to FT group, and cable to cable). How can inductance be lowered? Inductance is dependent upon: 1) number of ***turns*** (passes of conductor); 2) ***material*** (magnetic material increases inductance); 3) inductance ***area*** (FT dependent: area of shared magnetic influence); 4) inductance ***length*** (FT and non-FT); 5) filamentary ***winding*** (FT dependent: single versus multi-filamentary conductor); 6) ***mutual B*** (FT dependent: related to the distance from the B source, which for a cable is related to the width and distance between conductors). **Balanced FT**: (geometric symmetry of conductors with equal share of positions) greatly lowers inductance (see Figure 1). Creating balanced FT groups begins with creating an FT group (a set of linear media is arranged in FT configuration to each other and then connected in parallel). Multiple FT groups are then arranged symmetrically (such as in circumferential spirals with equal and constant wind angles as shown in Figure 2) which lowers inductance by canceling the induced emf and current in one full FT period of twist pitches with the opposing emf and current in another FT period from the same external transient B across both FT periods. Balanced FT groups are often lumped into logical phasing or geometries.

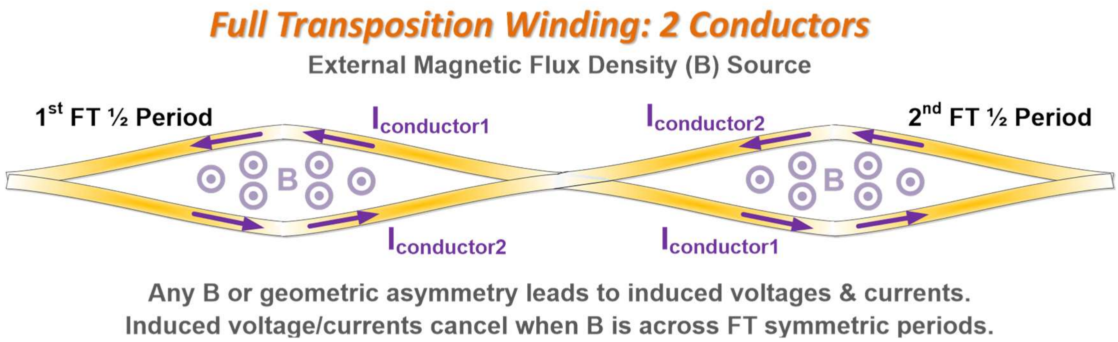


Figure 1: Induced conductor current canceled in one period for homogenous B

To further cancel **induced emf,** conductor groups can be arranged by both **opposing phases** and balanced FT by: 1) parallel connected ***wires/tapes in each phase per layer*** (see shorted tape bundle in Figure 3); 2) sets of ***phases per layer***; 3) ***across layers*** (including reverse winding and angling the twist angle between layers to increase FT canceling symmetry from the radius outwards). In this way the induced emf in one conductor per phase will cancel induced emf in an opposing conductor across the FT group periods. This emf canceling can minimize to remove a cable EM shield, which lowers complexity, diameter cost, and further inductance.

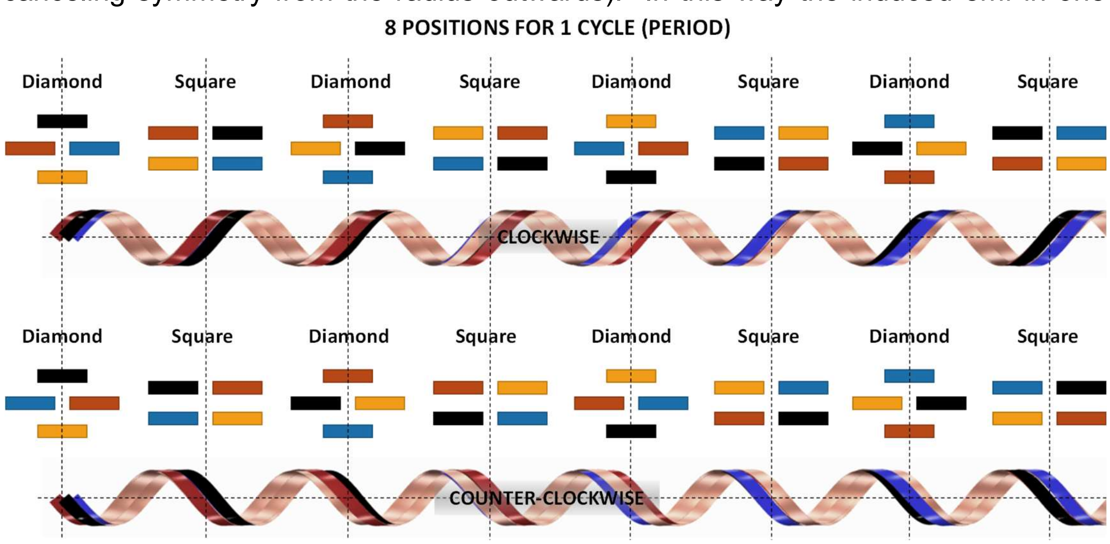


Figure 2: FT period diagram

Another means of lowering inductance is by minimizing the **inductance area** (see Figure 4). For FT groups, inductance area is a small area between the conductor groups being wound. For superconductor (SC) media, this inductance area further decreases to only between SCs due to the SC flux exclusion effect.

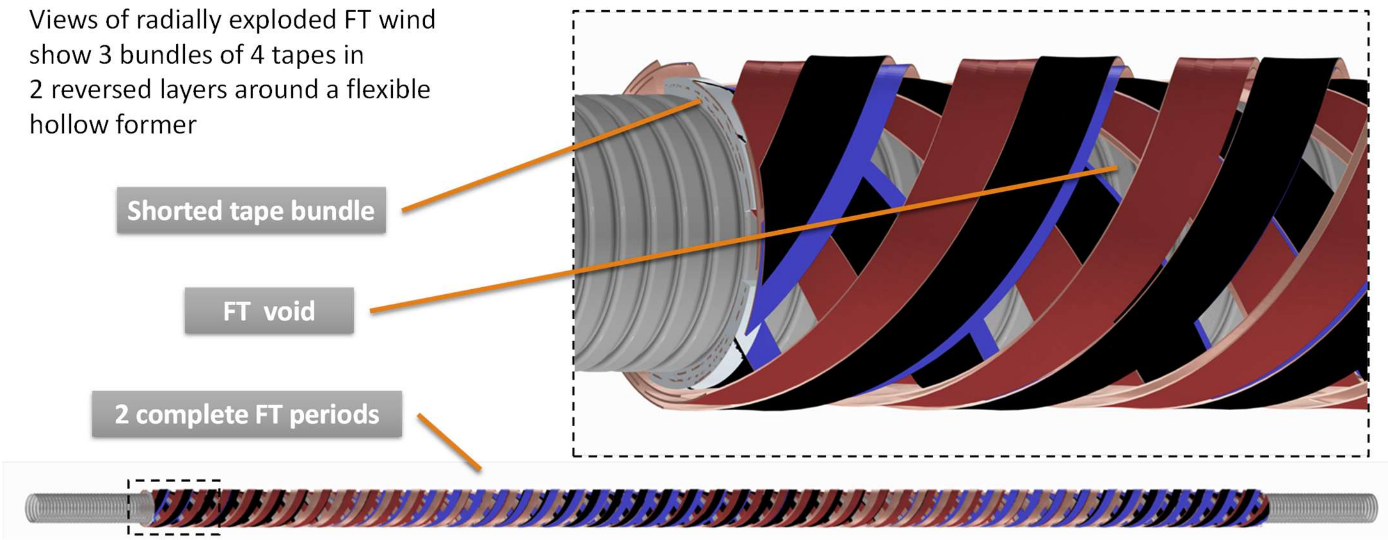


Figure 3: HTS Full Transposition 2-layer reversed wind with voids

PROBLEMS SOLVED

B self-field and nearby transient B: For an internal and/or external influencing transient B near any non-FT wind, such as a helical wind, all wound non-FT linear media magnetically link to one another and any outside magnetic influence. For this case, at most only partial transpositions can be achieved as layers increase (see Figure 5). This provides minimal emf canceling and current distribution symmetry which then leads to a much larger inductance than FT. Here the inductance area is the entire cable core area which is many orders of magnitude larger than the FT group area (see Figure 4). This increases cable core inductance and resistive losses, as the B leaves the conductor into the surrounding substrate producing inductive loop currents. For tightly packed winds of either SC (through B exclusion principle) or high frequency operation of conventional conductors, each overlapping layer of a helical wind also EM shields the adjacent layer. As conductors move positions in FT groups, a ***greater number of conductors share exposure to external B*** and adjacent FT groups, reducing per conductor induced currents. In an SC, a localized current and B must not exceed the SC critical current and B. This is similar to how non-uniform currents in conventional conductors have localized heating effects which limit power transfer. When inducing an emf into a set of SCs, lack of resistance maximizes the induced current. A high induced current in an SC diminishes its greatest benefit *(high current capacity)* due to the requirement of not exceeding SC critical current while superimposing all currents and considering non-uniform distribution. If the emf is not cancelled, induced voltage also superimposes which can locally exceed dielectric voltage. Current, B, and voltage cases limit power transfer. Any additional winding asymmetries or stress exacerbate these problems.

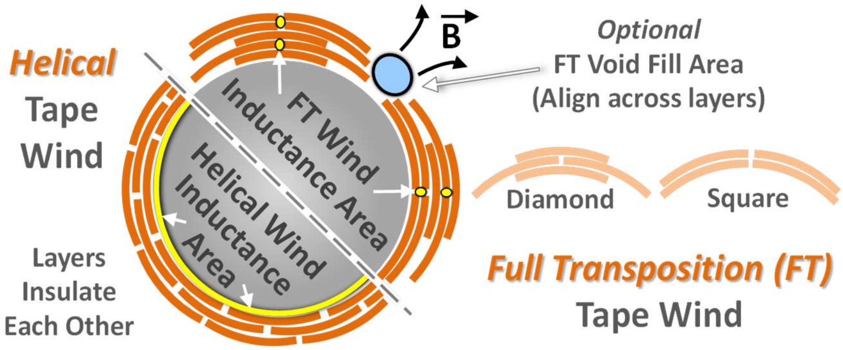


Figure 4: Helical 3 layers vs. SC FT 2 layers (cable cross section)

Undesired magnetic linking: The inductance of a magnet can magnetically link any asymmetries together. For any form of desired inductive power transfer, such as all toroidal and poloidal coils to the plasma of a fusion reactor, this increases transient times and power loss which reduces magnet to plasma linkage. For 2 adjoining current loops in a twist pitch, particularly within a layer (or in Rutherford cables), if the linked B is not balanced such as a geometric change or especially a changing B, the coupling currents extend beyond the pitch length. This extended current gives a very large inductance and B time constant increase, possibly orders of magnitude in the worst case of a non-FT wind. An ***FT cable core greatly reduces emf induced by asymmetry*** thus mitigating these negative effects.

In theory, FT leads to all conductors acting like a perfect set of parallel conductors, within manufacturing limitations. This ideal case is only true for shorter lengths between the end shorts. For long lengths there are numerous localized effects which are magnified by a high magnitude and transient B that is not uniform across the cable core long length. When an external B varies across many FT periods, a B averaging response occurs in the cable core which is further averaged for numerous turns of a cable magnet. Even for FT, a high B cable magnet still experiences some level of localized induced emf deviations across the cable core lengths prior to the core end shorting terminations. FT comes at the expense of a slightly lower power factor (pf) when using a low twist angle which slightly lowers power density and introduces possible conductor movement for unfilled voids. When the conductor is a tape such as high temperature SC (HTS) then the crossovers have sharper angles which limits compaction and introduces localized but minimal electrical crosstalk.

FT Technical Benefits

Full Transposition: 1) Removes non-FT ***current capacity*** limiting effects including limits against SC critical current; 2) Removes non-FT ***overvoltage*** limiting effects; 3) Supports uniform ***current distribution*** across the cable core and therefore cable magnet leading to a more uniform B (uniform current distribution also provides more efficient power transfer leading to a higher B); 4) Reduces ***AC losses*** (see next paragraph); 5) Has a superior ***mechanical modulus*** compared to cables with the same void fraction, particularly when winding structural material into the FT voids; 6) Lowers the ***inductive area*** of influence diameter (in a cable this is the diameter^2 term when the B path is axially much longer than the twist pitch and where diameter is usually less than 0.2mm between conductors in a group versus 10-150mm for the entire helical wind cable core, so an FT is orders of magnitude less cable reactance area of influence including conductor to conductor crosstalk and EM sent to and from the environment which also influences power quality; 7) Decreases ***inductive mismatch*** across layers (wind techniques that do not vary their wind angle between layers suffer increased inductive mismatch and FT has an inherently changing tape wind angle and a thicker single layer set of 3 or more HTS stacked tapes (diamond pattern) that naturally corrects for layer build mismatch thereby achieving better geometric inductance mitigation versus other wind types); 8) A ***reverse wind*** of FT layers (see Figure 5) provides partial transposition (B vectors due to currents partially cancel) further lowering inductance and external EM influences while greatly increasing structural support and electrical and thermal conduction paths when leaving voids; 9) Removing conductor to conductor and EM shield ***inductance induced losses*** reduces magnetic crosstalk reactance and provides no inductive mismatch or net self-field flux enclosed between the conductors.

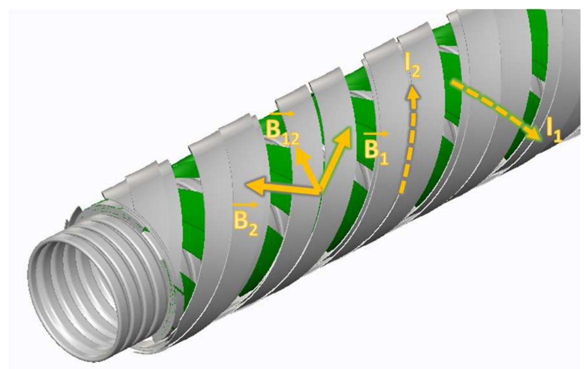


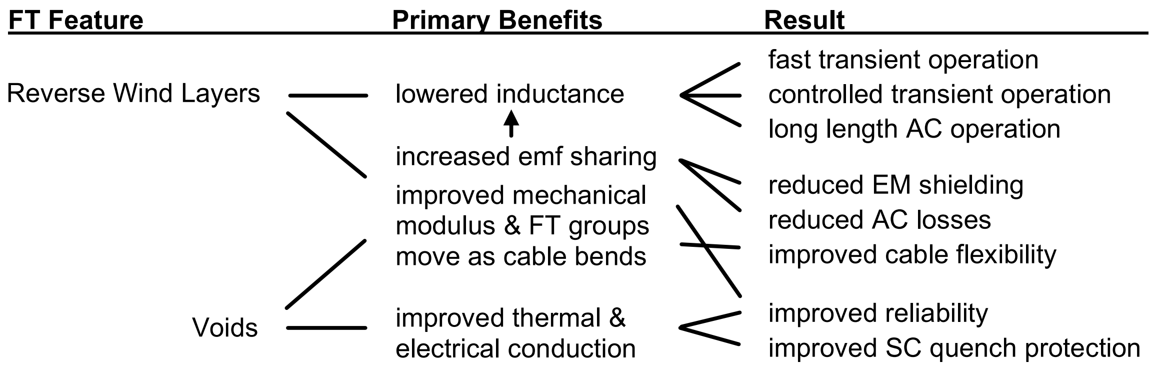
Figure 5: Layer 1 & 2 reverse wind direction

AC losses are a particular concern for SC cables. Hysteresis loss dominates coupling current loss for power cable AC loss. If an external B is large compared to the transport current, the current will move the electric center from the SC middle at 0 current to the edge at the critical current. Since the B must move twice as far, coupling AC losses are almost doubled. Since B must penetrate from the outside, tightly packed layers without FT are shielded from reducing these induced losses. The many B path orientations on any wound, versus flat, cable leads to lower AC losses. Further, ***the more FT and FT gaps alternate which HTS face and layer is in the B path, the more AC losses lower***. FT winds lower hysteresis self-field loss since the magnetization zone of each tape is kept as low as possible. FT allows the twist pitch to become the effective diffusion length thereby reducing trapped B and AC losses. The result is that FT HTS greatly reduces AC losses. HTS can have 20x less AC losses than similar multifilamentary SC wires that couple.

In summary, FT lowers AC losses and cancels emf and associated current distribution across parallel conductors terminated together, supporting: 1) faster ***transient*** operations; 2) increased ***conductor current***; 3) increased transmission ***efficiency***; 4) possible removal of ***SC EM shield*** layer; 5) ***quench*** protection.

Further Benefits of Full Transposition (FT) in Cable Cores Using Voids

In either a cable or magnet use case, FT conductor group separation can often increase to support design goals such as cooling, fault, quench, lower inductance needs, or increased useable B (see Figure 3 and Figure 4). Aligned **FT group separation** can provide: 1) improved ***electrical conductivity*** (fillers between uninsulated conductors during quench); 2) improved ***thermal conductivity*** (SC cooling path); 3) enhanced ***distribution of induced emf*** (considering a cross-section, voids expose a greater number of conductors to external B and adjacent FT groups across layers); 4) lowered ***inductance*** between FT groups (considering an FT group down the cable length, voids expose a greater number of FT groups across layers); 5) for cable magnets, high ***localized B coupling*** to an external B (voids create a coupling path, especially when aligned across layers); 6) increased **cable flexibility** (FT group movement over former as the cable bends).



Choice of Filler for Voids

Electrical and thermal conductive material is often placed around SC layers for protection, but in an HTS helical and stack wind the HTS ceramic, insulation, etc. thermally, electrically, and B insulates the layers which can lead to failure. FT can provide many times more efficient thermal and electrical conductive paths for quench protection and higher power operation such as further allowing AC to transient operation due to better cooling for transient heating. These cooling paths are purposely provided in FT group to group winding voids allowing cryogen flow or thermally conductive material to be wound or injected into the voids. Voids could be wound in direct, partial overlapping, or opposite alignment to allow direct cryogen cooling to all layers. On the inside of a corrugated hollow core, the turbulent cryo flow due to corrugations supports cryo flow thru the interlocking core into the FT void regions. Copper or solder (Sn63Pb37 or a lower than room temperature melt solder) filler into some or all voids provides direct electrical and thermal layer conducting paths while also providing structural support. By orienting an internally wound, injected, etc. thermally conductive material, the wound cooling paths optionally connect to an outer liquid or conductive cooling path at repeated lengths down the cable, such as 0.1m mesh contact also allowing FT internal cryogen flow. Dielectric, structural, and controlled fault power flow needs separate FT thermal and electrical conductive flow options into appropriate groupings. If cooling and power flow are adequate, then voids can be similarly filled with only a dielectric and/or structural supporting material. If coupling losses with electrical conductor FT filled gaps is a concern, then a thermally conducting dielectric polymer filler is considered.

Quench Protection

All SC devices must **safely quench** and recover to full operation. In a quench situation, direct and induced currents plus a high thermal and/or magnetic "hot spot" can lead to heating and large forces which can damage a device. Quench protection designs must account for the quench energy, current induced magnetic forces, SC to non-SC transition mode thermal and current conductor paths, dielectric integrity, pressure rise, and any associated thermal "hot spot" such as a solder joint. Device design involves a choice between insulated and non-insulated SCs. Each choice has pros and cons. Insulated SC is often used to remove (dB/dt), [d(Voltage)/dt], and uncontrolled quench paths leading to single burnout points but suffers from thermal instability and quench propagation. Uninsulated HTS supports transport current bypassing a local "hot spot" to help prevent thermal instability and quench propagation but is susceptible to induced magnetic energy. By separating conductor groups in the cable core, FT voids can be used to mitigate problems from induced energy in uninsulated SCs and support a design with their quench protection benefits.

Conclusion

Balanced full transposition and the use of group separation (or voids) are the best means of lowering inductance in wound cables operating in transient current and magnetic applications. Lower inductance delivers:

- Lower impedance
- Faster transient response

In superconducting cables, lower inductance also delivers:

- Reduced AC losses (even greater benefit than for conventional conductors)
- Quench protection

A comprehensive relationship of full transposition benefits is shown in the following chart.