

Superconducting Transformers Using Continuously Transposed Cable

A General Cable Superconductors White Paper

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February 2009

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ABSTRACT

Many High Temperature Superconductor (HTS) transformer designs have been attempted but none look attractive due to the lack of a suitable superconductor. The BSCCO wire¹ was too lossy and the 2G wire² currently available in a standard 4mm width, does not carry sufficient current to enable large transformers. However, a continuously transposed cable (CTC or Roebel Cable) currently under development by General Cable Superconductors makes large transformers feasible. The CTC uses 2G wire which will be commercially available from sources in the US, Europe and Japan. The CTC can carry large current while keeping AC losses within acceptable limits. This paper describes a 50MVA, 132kV/11kV transformer preliminary design utilizing CTC. This HTS transformer is expected to be 1/3rd weight, 1/4th foot-print and 1/5th volumetric size of a conventional transformer of similar rating. This transformer also has low leakage reactance (7%) which allows serving loads with minimal voltage regulation. The normal operating temperature of the transformer is 77K. It could carry up to 100% over-load indefinitely (without loss of life) if operated at 66K. There is no fire hazard because an HTS transformer uses inert liquid nitrogen as a coolant and it could be employed inside high rise buildings and wind turbine nacelles without any undue risk. These transformers are also environmentally friendly because they use less material. Transformer cost is difficult to estimate accurately at this time due to inadequate 2G wire cost data and the cost of conversion into CTC. Because of the high cost of development, HTS transformer technology should be initially demonstrated in smaller distribution level transformers. A design for a 1MVA transformer is also discussed in this paper for demonstrating HTS technologies and its operation in an electric grid. HTS transformers of 5-10MVA could be considered for off-shore wind turbine generators where the transformer must fit in the nacelle and operate reliably for extended periods of time and in shipboard and rail-road applications.

¹ BSCCO-2223 wire made using powder-in-tube technology, sometimes called 1st Generation (1G) wire

² YBCO-123 or (RE)BCO -123 wire made using coated conductor technology, often called 2nd Generation (2G) wire

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1. INTRODUCTION

During the last 10 years, many manufacturers attempted to prototype transformers using BSCCO wire but were unsuccessful due to the low current carrying capability of the wire and its high AC losses. Most developers concluded that a low loss HTS wire is a prerequisite to development of a practical HTS transformer. Now 2G wire is available from sources in the US, Europe and Japan, which intrinsically has lower loss when oriented parallel to the local magnetic field and is amenable to strategies for reduced perpendicular field losses. Available standard 4mm wide wire carries about 100A and is not suitable for manufacturing large transformers. Wider widths (up to 10-40mm) are also available as custom orders but they do not fit standard transformer manufacturing processes and the wider widths are likely to be too lossy. Thus a technology is needed to adapt 2G wire for use in transformers. The continuously transposed cable (CTC) technology makes this feasible. Industrial Research Ltd (IRL) has been developing manufacturing processes for CTC using commercially available 2G wire¹. IRL and General Cable Corporation have formed General Cable Superconductors Ltd to manufacture CTC commercially for use in HTS magnets, transformers and other power equipment.

A CTC cable carries large current while keeping AC losses within an acceptable limit. This white paper presents transformer designs illustrating how CTC can enable practical HTS transformers. It presents a preliminary design for a 50MVA transformer for application in electric utility systems. In order to limit the cost and risk of developing a large 50MVA unit, it is likely smaller units will be deployed to demonstrate the technology. A preliminary design for a smaller 1MVA distribution transformer is presented as a potential development path for the technology and as a reference to illustrate the benefits of scaling to larger power ratings. The 1MVA prototype transformer employs CTC and manufacturing technologies typical of large transformers. The 1MVA, 3-phase HTS transformer is designed for an 11kV/420V distribution grid. It employs a CTC conductor, windings fabricated using conventional transformer manufacturing practices and an integrated cryogenic system for demonstrating improved efficiency compared to previous HTS transformer demonstrations.

The 50MVA transformer is expected to be about ½ size and ½ weight of a similar rated conventional transformer and has comparable efficiency. It is capable of carrying 50% overload for an extended period of time (at 70K) and 100% overload (at 66K) without loss of life. This is a definite advantage of HTS transformers over conventional transformers. The HTS transformer has certain limitations which prevent it to fully meet current IEEE² or IEC³ standards. These issues are discussed later in this paper.

2. CTC CONDUCTOR CHARACTERISTICS

CTC employs Roebel cable conductor construction that has been used in AC electric machines for a very long time. A Roebel cable consists of a number of wide strands bent laterally with a certain periodicity and then assembled such that each strand occupies all possible locations over a given length of the cable. 2G wire cannot be bent laterally but it can be cut to form a strand of a Roebel cable. Figure 1 shows the steps in construction of a CTC. The cable is labeled using the convention number of strands/strand width in millimeters. The necessary number of strands can be assembled to achieve a desired current in a CTC. AC losses in a CTC are the sum of losses in individual strands plus a small loss due to magnetic coupling among strands. IRL is developing formulae for estimation of AC losses by conducting measurements on coils built with CTC. Currently, General Cable Superconductors is manufacturing CTC using 2mm and 5mm wide strands. The transposition pitches for these cables is 90 and 300mm respectively. It is possible to assemble 2mm wide 10 strands (10/2) and 5mm wide 15 strands (15/5) CTC conductors. Other combinations are possible with straightforward changes in tooling.

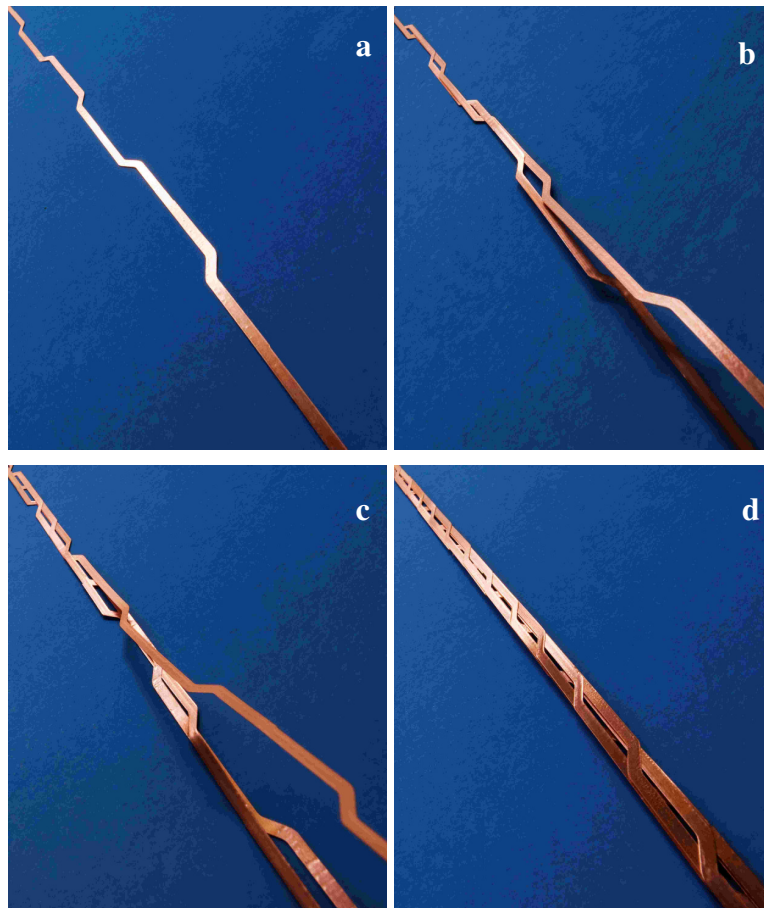


Figure 1: Winding of CTC a) single strand b) winding in second strand c) winding in third strand d) completed cable

3. TRANSFORMER REQUIREMENTS

A power transformer intended for operation in an electric utility grid is required to meet all requirements of industry standards such as IEEE and IEC. High voltage requirements could be satisfied in HTS transformers using design approaches employed in the construction of conventional transformers. However, it is challenging to withstand transient currents during short-circuit faults and switching operations. For example, a conventional distribution transformer is normally designed to withstand short-circuit currents for up to 2 seconds (Sect. 7.1.3.1 of IEEE Std. C57.12.00-2000²). Also when a transformer is connected to a grid, it draws a large current which can persist for a long period of time. These transient currents are generally >10x rated currents and are capable of driving the HTS windings to their normal state. It would be necessary to take precautionary steps while interfacing and operating an HTS transformer in an electric grid.

4. TRANSFORMER CONCEPTUAL DESIGN

A conceptual design of a 50MVA, 138kV/11kV transformer is developed below to identify component technology development and performance issues. Basic requirements for a 50MVA transformer are listed in Table 1. In order to demonstrate the technology and retire risks of developing the 50MVA transformer, a 1MVA, 11kV/420V distribution transformer was also sized. The requirements for this 1MVA unit are listed in the table.

The HTS transformer design is based on the following major assumptions.

- i. Both primary and secondary windings employ CTC made of 2G wire.
- ii. Primary winding employs 8/2 CTC (8 strands x 2mm wide) and has a critical current of 448A in self-field at 77K⁴.
- iii. Secondary winding employs 17/5 CTC (17 strands x 5mm wide) and has a critical current of 2380A in self-field at 77K.
- iv. The iron core is similar to that employed in conventional transformers and operates at room-temperature.
- v. Primary and secondary windings of each phase are housed in individual liquid-nitrogen vessels.

Table 1: HTS Transformer Specifications for 50MVA and 1MVA units

Parameter	50MVA	1MVA
Rating, MVA	50	1
Primary line voltage, kV	132	11
Primary connection type	Delta	Delta
Secondary line voltage, V	11000	420
Secondary connection type	Star	Star
Frequency, Hz	50	50
Cooling	Liquid N ₂	Liquid N ₂
Continuous overload capability	50%	50%
Operating temperature, K		
Normal load	77	77
Over load	70	70
Insulation Qualification		
AC voltage with stand, kV	330	28
BIL (IEEE Std. C57.12.00-2000, Table -4), kV	550	95

The 50MVA HTS transformer elevation and plan views are presented in Figure 2. This transformer uses 7.6km of 8/2 CTC for the primary winding and 1.1 km of 17/5 CTC for the secondary winding. The primary winding could be constructed using layer or continuous pancake winding techniques. Each secondary winding consists of two layers and is constructed using a layer winding configuration. The HTS transformer is 1.26m wide (W), 3.31 m long (L) and 3.26m tall (H). A comparable rating conventional transformer has WxLxH of 2.29m x 6.40m x 4.57m. On this basis, the HTS transformer width and length are about ½ of the conventional transformer and its height is ~30% less than the conventional transformer. The HTS transformer weighs about 26 kkg, which is about 1/3rd the weight of a conventional transformer.

The life of a conventional transformer is usually determined by the life of electrical insulation, which in turn is governed by operating temperature and time operated in overload conditions. However, an HTS transformer would have an unlimited life since it always operates at cryogenic temperature even during overload conditions. HTS windings contained in a liquid nitrogen (LN₂) vessel are operated at ~70K under 3-4 bar pressure. A system to achieve sub-cooled LN₂ in the winding vessel is shown in Figure 3. The LN₂ is cooled in a separate cryostat with cryocoolers using the

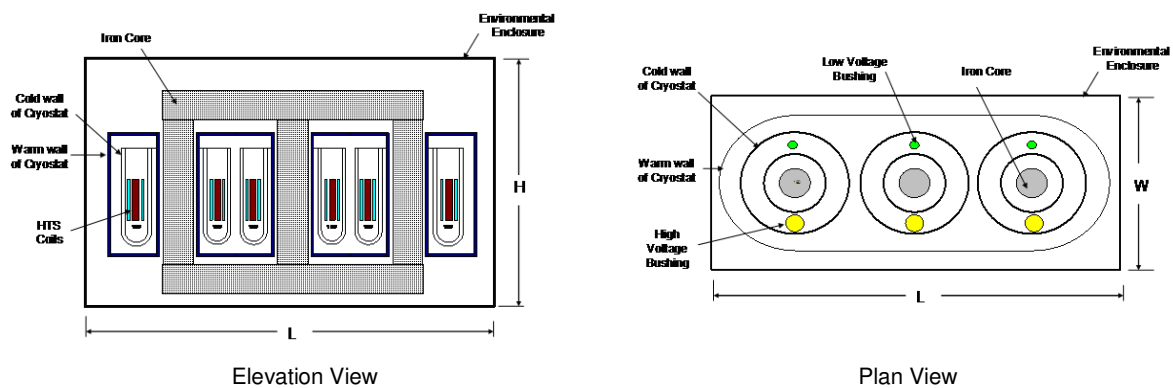


Figure 2: 50MVA HTS Transformer Outline

arrangement shown in the figure and pumped to the winding vessels. One pump can be used for pumping LN₂ to all winding vessels. The temperature of LN₂ is controlled by controlling the temperature of cryocooler cold-heads. Excessive cooling power will lower the temperature of LN₂, which is preferable from the view point of gaining extra safety margin to carry over-load. In an actual system, a heater is installed on the cold-heads to keep their temperature above the freezing temperature of LN₂ to prevent icing. Such systems have been successfully built and operated by Oak Ridge National Laboratory and others.

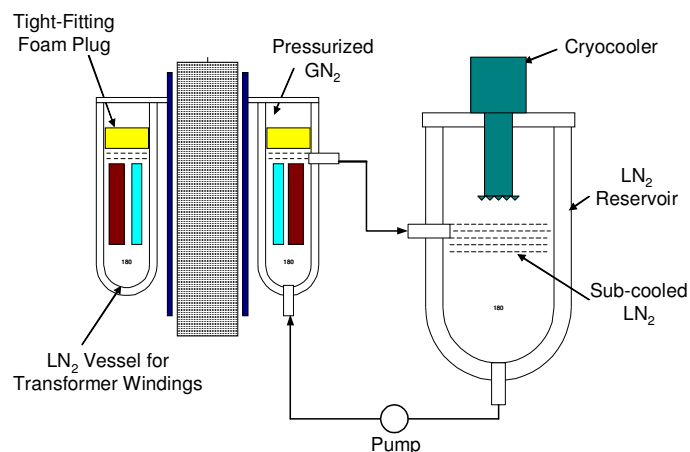


Figure 3: Cooling System Configuration

Key challenges for manufacturing a 50MVA transformer are the construction of CTC, coil winding using CTC, cryostat consisting of LN₂ vessels, cooling system, and assembly and operation. To minimize risk represented by these challenges, we present a design for a smaller scale demonstration transformer. The transformer is rated 1MVA, 11kV/420V for a 50Hz distribution grid and its specifications are included in Table 1. The HTS transformer can be operated at 77K for normal use and could carry 50% overload indefinitely if cooled to 70K by providing extra cooling. It could carry 100% overload if operated at 66K. Thus a range of overload possibilities exist as a function of available cryogenic cooling power. The prototype can be subjected to all factory and customer testing as per IEEE and IEC Standards and other applicable standards of the hosting utility.

5. PERFORMANCE

Since HTS windings are more compact than copper windings of a conventional transformer, the leakage reactance of HTS transformers could be designed to be low. A low leakage reactance results in lower output voltage variations between no-load and rated-load conditions. It might also be possible to eliminate use of tap changers typically employed to correct output voltage as a function of load. However, lower leakage reactance generates higher transient currents and forces during a fault near the transformer. Thus a compromise is needed between lowest leakage reactance and acceptable fault currents. Magnetizing reactance tends to be higher for HTS transformers than conventional transformers – which is a desirable trait. Transient currents during a fault and during switching represent significant challenges. These are discussed below.

Transient Currents During a Short-Circuit: Per IEEE Standard³, a Category II HTS transformer is expected to withstand a terminal fault for a period of 2 seconds. Once the circuit with fault has been isolated the transformer is required to keep serving the healthy circuits, i.e. the circuits without the fault. In order to satisfy this requirement in the 1MVA transformer, it would be necessary to co-wind 30mm total thickness of copper (stabilizer) tape within a CTC. However, thicker copper tape would occupy more space and will impact the transformer size and weight. This would also erase any size and weight advantage with respect to a conventional transformer. AC losses in the thicker tape might also be unacceptable

In order to seek a solution to the above challenge, the temperature at the end of a 2 second fault was calculated with different thicknesses of copper tape co-wound with a CTC in the secondary winding. The temperature at the end of a 2-second fault is higher when the copper stabilizer thickness is small. For example, with 8 mm thickness of copper stabilizer, the HTS temperature will rise to 324K at the end of a 2 second fault whereas 30 mm thick stabilizer will limit the temperature to 90K. In order to let a transformer bear rated load just after a fault has been cleared, it is essential to limit the temperature of the HTS windings to less than 90K during the fault. On the other hand, if the windings temperature is higher than 90K, it would be necessary to allow the windings to cool down to 77K (normal operating temperature) before letting them bear the load. A possible solution is to use 4 mm thick tape and limit the fault duration to 0.1 second. This scheme would require reprogramming of the protection system for the transformer.

Transient Currents During Switching: When a transformer is suddenly connected to an electric grid, it draws a large inrush current for magnetization of the iron core. This current could be more than 10X normal current and can persist for a long time. This high current could quench the HTS winding, which has then to be cooled back to its superconducting state before it is allowed to carry any load current. This will require significant downtime before the transformer is available for load bearing. It is possible to minimize the switching current by switching each phase of the primary winding individually and at the moment when the system voltage wave is between 120° and 180° (angles are measured from the instant when the voltage is zero). With this approach, the transient current could be reduced to 1-2% of the nominal current of HTS windings. In order to achieve this, it would be necessary to employ circuit breakers with individual phase control capability. This issue has been addressed in the literature^{5,6,7}.

6. VALUE PROPOSITION

HTS transformers provide several benefits compared to a conventional transformer. Some of these benefits are discussed below.

- Smaller size enables application of these transformers where compactness is important. Some of the possible applications are inner city substations, high rise buildings, wind turbine nacelles, ship systems, and rail roads.
- Lighter weight is important for ease of transportation. For remote locations where adequate roads do not exist, HTS transformers are easier to transport. Less weight is also attractive in many of the applications mentioned above.
- Higher efficiency is important in almost all applications. It saves operating cost by reducing fuel used for power generation and by reducing greenhouse gas emissions.

- Since HTS transformers employ inert liquid nitrogen instead of flammable oil the fire hazard is almost eliminated. However, special arrangements are needed when an HTS transformer is employed in a closed space to avoid suffocation due to a fault that could cause rupture of the liquid nitrogen container and gaseous nitrogen diluting the oxygen content in the air.
- HTS transformers, free of oil, could be employed indoors. This feature is attractive for inner city substations, wind turbine nacelles and ship systems.
- More compact and lighter HTS transformers save meager natural resources and further curtail greenhouse gases generated during manufacturing of these materials.

HTS transformers look attractive for a broad spectrum of applications and could provide benefits to both manufacturers and users. Manufacturers benefit by doubling the size of their current transformers without having to add factory space and handling equipment. Users benefit by reduced operating cost and lower capital cost of infrastructure due to the smaller space required by an HTS transformer.

7. TECHNOLOGY EVOLUTION/READINESS

Technologies needed for manufacturing HTS transformers have already been demonstrated or are in the process of being demonstrated. Below is the status of key technologies needed for manufacturing HTS transformers.

- HTS Wire: 2G wire needed for transformers is available commercially from sources in the US, Europe and Japan. Its current price is high but is expected to drop to the range of \$25-50/kA-m as demand for the wire increases and technology improvements are made.
- CTC Conductor: Is available commercially from General Cable Superconductors. Piece lengths are limited by the piece lengths of wire available or up to 400m if splices are acceptable. Price and efficiency of CTC manufacture will improve as demand for HTS transformers and other power equipment increases. Besides transformers, CTC could be used for motors and generators, fault current limiters and a variety of magnet systems.
- Winding Construction: HTS coils have been built and successfully tested in a variety of devices consisting of motors and generators, transformers, fault current limiters and magnet systems. Winding fabrication technology has been demonstrated in small/medium size devices but it needs adaption to manufacturing of transformer windings in a factory setting.
- Cryostat: HTS windings are housed in non-metallic vessels containing liquid nitrogen for cooling. Such non-metallic vessels have been successfully built worldwide for many transformers and other applications.
- Cooling System: Liquid nitrogen cooling systems have been demonstrated in many projects. A closed loop liquid nitrogen refrigeration system could be built using available off-the-shelf cryocoolers. These are modular devices and could be serviced while the transfer remains in operation and keeps servicing the load.
- Iron Core: The iron core to be used in the HTS transformer is the same as that for the conventional transformers. For the same size unit, the HTS transformer will use less than ½ the iron core than that for conventional transformers.
- Bushings: Standard paper/epoxy bushings used in conventional transformers could also be used for the HTS transformers.

Prior to developing capability to build larger units (>50MVA), it is necessary to first demonstrate the technology in smaller units (1-5MVA). These smaller units could employ technologies typical of the larger units. Considerable market potential also exists for smaller units for applications in inner city substations, wind generator nacelles, ship systems, and high rise buildings.

8. CONCLUSIONS

We have presented a design for a 50MVA HTS transformer to illustrate the benefits possible from using HTS and in particular the benefits of incorporating CTC. A smaller 1MVA transformer is also described which could be constructed as part of a development path for demonstrating this technology.

¹ *Progress in the Manufacture of Long Length HTS Roebel Cables*, R.A.Badcock, N.J.Long, M.Mulholland, S.Hellmann, A.Wright, and K.A. Hamilton, presented at ASC 2008, accepted for publication in proceedings; *Narrow strand YBCO Roebel cable for lowered AC loss*, N J Long, R Badcock, P Beck, M Mulholland, N Ross, M Staines, H Sun, J Hamilton, R G Buckley, Journal of Physics: Conference Series 97 (2008) 012280

² IEEE Std. C57.12.00-2000 'IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers'

³ IEC 60076-3 and -4 'Power Transformers'

⁴ The CTC critical currents are based on a wire $I_c=280A/cm$ and do not include the reduction in a cable due to self-field. The J_c scaling in field is included in J_c calculated for the windings based on data available from the wire manufacturers and measurements at IRL.

⁵ S. J. Asghar, 'Elimination of inrush current of transformers and distribution lines', Proceedings of 1996 International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, Vol. 2, January 1996, pp. 976-980, held in New Delhi, India, ISBN 0-7803-2795-0

⁶ US Patent # 7095139

⁷ T. Ishigohka, K. Uno and Sakio Nishimiya, "Experimental study on effect of inrush current of superconducting transformer", IEEE Trans. on Applied Superconductivity, Vol. 16, June 2006, pp. 1473-1476