ABSTRACT

Superconducting transformers have advantages over their conventional counterparts, making them a killer technology in electric power grids and renewable energy systems, as well as transportation applications requiring high power transmission capacity. Compared to conventional transformers, superconducting transformers offer low weight, small size, high fault tolerance, fault current limitation, significant overload capability, and no environmental issues or fire hazards. Power systems and microgrids are candidates for the implementation of superconducting transformers when they include distributed generation and renewable energy, especially wind farms. Transportation applications also benefit from the highly compact structure and lightweight superconducting transformers. This paper introduces opportunities offered by superconducting transformers for supplying power with high reliability, stability, and safety.

KEYWORDS:

Compact size, Fault tolerance, Mobile transformer, Superconducting transformer, Traction transformer, high-temperature superconductors (HTS), YBCO.

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Superconducting transformers for power, energy, and transportation applications

An introduction to superconducting technology for transformer engineers

Critical conditions define a boundary for a superconducting state, and any breach from them results in the transition of superconductors into a non-superconducting state

In the DC regime the resistivity of superconductors and, therefore, losses are zero, but in AC mode, on the other hand, a slight resistivity appears and causes a shallow AC loss in superconducting devices

1. Introduction

1.1. Superconductivity

Superconductivity is a phenomenon that is defined as "*the property in some specific substances or composition of materials - e.g., specific alloys - in which electrical resistivity is completely or partially vanished and magnetic fluxes are expelled out, under specific conditions*" [1]. These specific conditions are known as "critical" conditions which consist of critical temperature (T_c), critical current density (J_c), critical magnetic field (H_c), and critical tension stress (σ_c). These critical conditions define a boundary for superconducting state, and any breach from them results in the transition of superconductors into a non-superconducting state. Electro-magneto-thermal critical conditions of superconductors are shown in the diagram of Figure 1. As shown in this figure, by exceeding a critical condition, superconductors transit into another state (so-called normal metal state) with very high resistivity. This specific property of superconductors results in a new concept for fault current limitation in power applications.

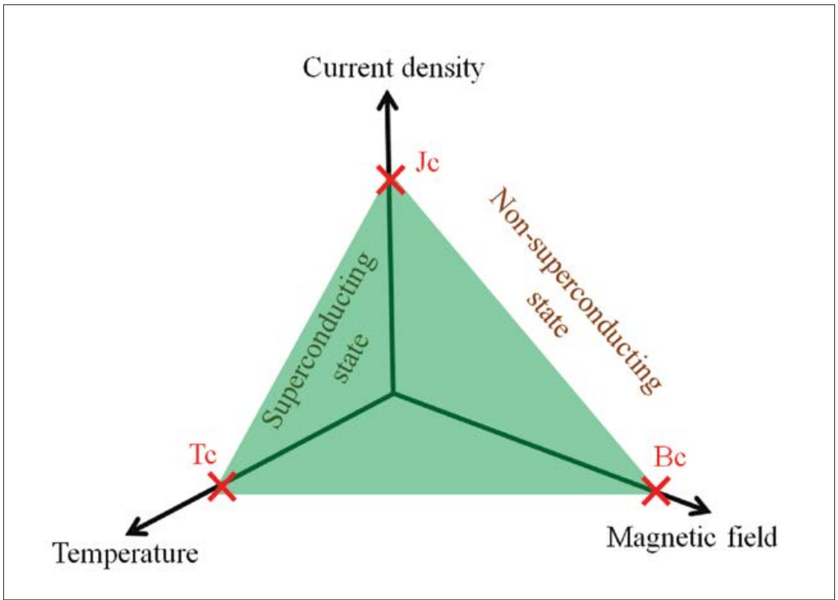

Figure 1. Critical conditions of superconductors

Generally, in the DC regime and below Tc, the resistivity of superconductors and, therefore, losses are zero. In AC mode, a slight resistivity appears and causes a shallow AC loss in superconducting devices. Regardless of their critical temperature, superconductors can carry much higher current density than conventional conductors such as copper or aluminum. Generated AC loss in superconductors is much lower than ohmic losses in copper or aluminum wires. However, critical current density in superconductors depends on temperature and magnetic fields; consequently, current carrying capacity changes, if temperature or external magnetic fields change. Figure 2 illustrates the critical currents of a typical superconductor below a temperature of 65 K at different magnetic flux densities, where J_c is reduced when the magnetic field intensifies.

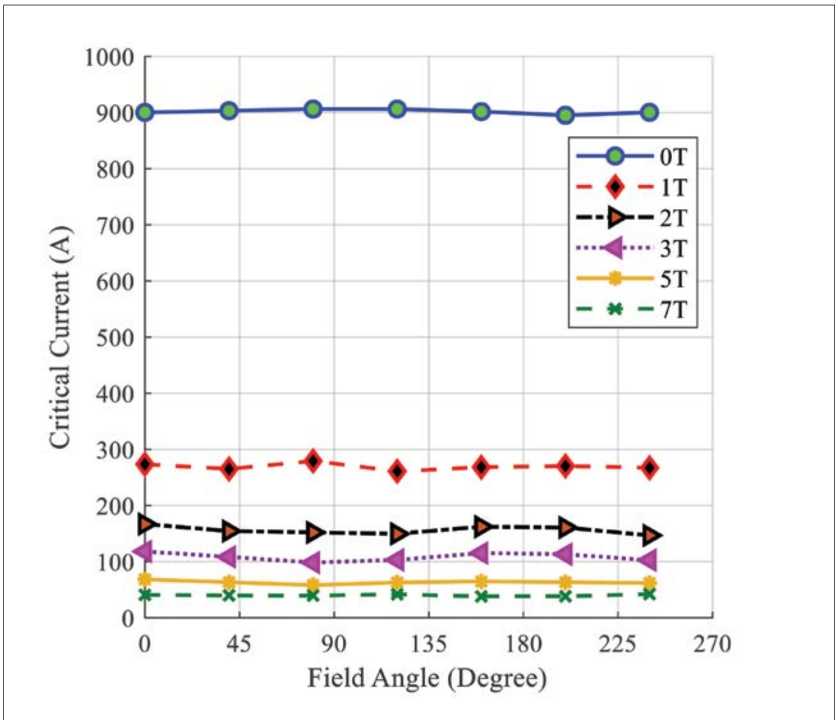

Figure 2. Magnetic flux density dependency of critical current in a SuNAM SAN04200 2G HTS tape, 4mm wide and 0.1mm thick [2]

Superconductors in the form of coils, windings, and cables offer a solution to the engineering challenges of modern power and energy systems

TABLE 1. The properties of conventional conductors and YBCO superconductors [4], [5]

Conductor	Typical current density (A/mm^2) @ 77K	Cost range	Density (g/cm^3)	Electrical conductivity (S/m)
YBCO	20,000-70,000	High and Very High	6.3	$>10^{14}$
Copper	500-1,000	Medium	8.93	(58-60) $\times 10^6$
Aluminum	300-800	Low and Medium	2.7	(37-40) $\times 10^6$

Given the advantages of superconductors, HTS and LTS materials were used to fabricate electric devices for power applications, such as busbars, cables, electric machines, storage units, and transformers

Table 1 compares the cost, current density, and material density for a well-known superconductor commercially available in long lengths, e.g., Yttrium Barium Copper Oxide (YBCO), with conventional conductors [3]. Note that copper and aluminum prices are reported based on average variations over the previous 5 years [4], [5].

Superconductors in the form of coils, windings, and cables offer a solution to the engineering challenges of modern power and energy systems. The very low resistivity of superconductors is one reason that engineers use them to develop and fabricate power apparatuses such as electric machines, transformers, and cables. By using superconductors, not only energy loss is reduced but also the resiliency, reliability, and stability of power and energy systems improve. Superconductors are fabricated in very thin tapes with extremely low weight and size, which reduces the final size and weight of power apparatuses. In addition, the high current carrying capacity of superconductors can dramatically improve the power density of electric devices, i.e., the size of superconducting devices is smaller than conventional alternatives. These advantages have resulted in numerous Research and Development (R&D) projects, especially in aviation, marine, space, energy, and power sectors.

Based on the critical temperatures of superconductors, they are classified into two main groups: Low-Temperature Superconductors (LTS) and High-Temperature Superconductors (HTS).

Based on critical temperatures of superconductors, they are classified into two main classes: Low-Temperature Superconductors (LTS) and High Temperature Superconductors (HTS). LTS usually operates around the temperature of Liquid Helium (LHe), i.e., 4.2K, while HTS usually operates below the boil-off temperature of Liquid Nitrogen (LN_2), i.e., 77K. Obviously, LTS materials require massive cooling power to keep them at cryogenic temperature, especially in AC power applications. This makes them expensive and impractical for use in power applications such as cables, transformers, and fault current limiters. HTS materials are preferred for large-scale power applications because of their large current carrying capacity. HTS materials are further categorized into two subclasses: the first is superconducting wires or filaments based on bismuth, known as first-generation (1G) HTS tapes/wires. The second subclass is made from rare earth metals, known as second-generation (2G) ReBCO HTS tapes [6].

The 2G ReBCO tapes have higher current carrying capacity relative to LTS materials and lower cooling costs. These properties make them better choices for applications in power systems and transportation. Moreover, LN_2, the common cryogenic fluid for ReBCO tapes, is not flammable or explosive. In addition, gaseous nitrogen generated by heat loads of

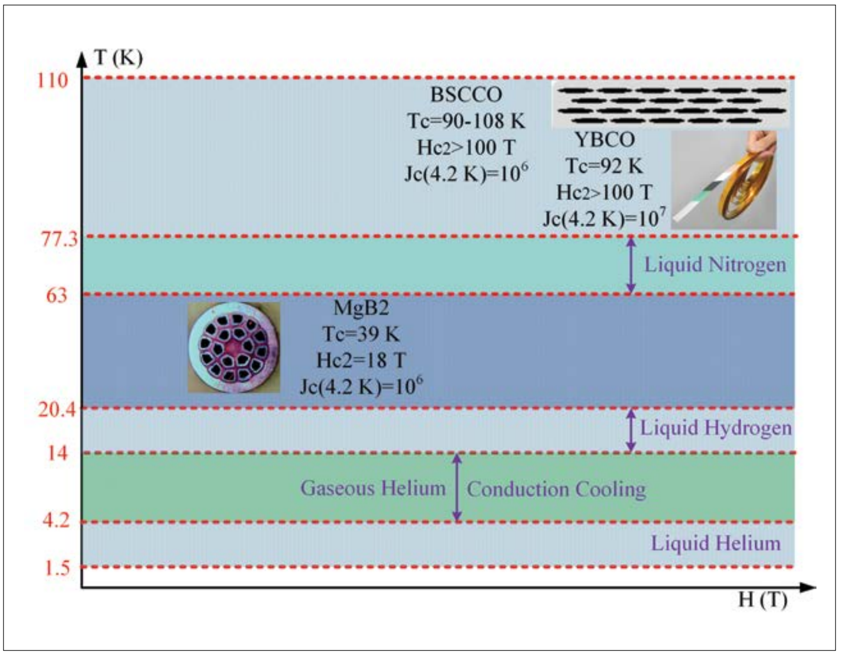

Figure 3. Classification of the suitable superconductors for power applications based on critical temperatures and magnetic fields

Figure 4. The offshore wind farm of the Seagreen project [17]

Cryogenic fluid also plays a role as a coolant to maintain and stabilize the operating temperature of transformer windings at base temperature by dissipating winding AC losses

superconducting windings could simply be released into the air without environmental risk or toxic effects. Also, the main source of gaseous nitrogen is the atmosphere, where it is abundant gas at 78%. In practice, liquefying this gaseous nitrogen is already a source of LN_2. This makes LN_2 one of the cheapest cryogenic coolant fluids. More details about the classification of superconductors are shown in Figure 3.

1.2. Superconducting transformer proofs-of-concept and demonstrators

Given the advantages of superconductors, HTS and LTS materials were used to fabricate electric devices for power applications, such as busbars, cables, electric machines, storage units, and transformers [7] on a prototype scale. A 3-phase, 1 MVA, 11/0.415 kV HTS power transformer demonstrator was developed at Robinson Research Institute, New Zealand, where PB Power, Vector & North Power, ETEL, and Wilson Transformer were industrial partners. The transformer's active part efficiency was reported as 99.95% at full load, and 99.997% at half load operation. The total efficiency of the transformer, including the cooling system, was about 98.6% and 99.9%, respectively [8]. In addition, other demonstrators include a 1 MVA, 13.8/6.9 kV HTS transformer in USA, a 3 MVA, 22/6.9 kV single phase HTS transformer in Japan, and a 45 kVA, 2.4/0.16 kV HTS transformer in China [9]. In 2015, a single phase 577 kVA, 20/1 kV HTS transformer was built in Germany in cooperation between Karlsruhe Institute of Technology (KIT) and ABB. Also, a 45 kVA single-phase HTS transformer with fault tolerance capability was developed and tested successfully at Robinson Research Institute, New Zealand [10]. As one of the recent developments of HTS transformers in the transportation sector, a single phase 6.6 MVA, 25 kV traction HTS transformer was fabricated for use in high-speed bullet trains in China [11], [12]. The objective was to minimize AC losses in the HTS transformer to decrease the size of the cooling system and reduce the total weight of the transformer by half. By doing so, efficiency was also enhanced, reaching 99.5%.

Projects for proving the feasibility of HTS transformers for enhanced efficiency may motivate the industry to invest more

Considering fault limitation and tolerance, extended overload endurance, and environmentally friendly liquids, HTS transformers are a promising solution for offshore wind farms

funds dedicated to increasing the Technology Readiness Level (TRL) of HTS transformers for power and renewable energy systems and transportation applications [13]. It should be noted that the TRL level of HTS transformers is currently in the range 4-6.

In the next 10 years, the cost of superconductors at about 220-230 US$/kA.m today for YBCO could be significantly reduced to around 50 US$/kA.m

The iron core lays outside of the cryogenic environment and works at room temperature. This structure is the most efficient among the warm-core, cold-core, and conduction-cooled types. Superconducting tapes are laid inside the cryogenic environment to form windings. The YBCO tapes are the most promising tapes for use in HTS transformers because YBCO windings require lower cooling costs (as they have high T_c) and are produced and commercially available in long lengths. In addition, critical current in YBCO tapes drops less sharply with field and temperature increases compared to other 2G superconductors. Cryogenic fluid plays the role of thermal and electrical insulation. This fluid is usually selected based on the operating temperature required by the HTS tape.

Cryogenic fluid also plays a role as a coolant to maintain and stabilize the cryogenic temperature of superconducting windings of HTS transformer by dissipating losses and heat loads in the transformer tank, a so-called cryostat. Warm fluid (due to AC losses and other heat loads) is transmitted to the cooling system [14]. Liquid Hydrogen (LH_2), LN_2, LHe, and Gaseous Helium (GHe) are the most common types of cryogenic fluids used for HTS tapes in commercial applications, from superconducting MRI magnets to particle accelerators. However, LN_2 is the most common and cheapest for large-scale power applications, including HTS transformers. A cryostat is designed to maintain fluid within a specific temperature range, avoid heat leaks, minimize pressure fluctuations of cryogenic fluid, and tolerate temperature gradients between cryogenic temperatures and surrounding temperature. More information about the elements of the cooling systems is discussed in [15].

It is unfair to compare HTS transformers directly with conventional oil-immersed transformers solely on the initial purchase price, so the total ownership cost is used to compare these two types of transformers

The United Kingdom (UK) has a high potential for power generation by offshore wind farms, where a high amount of electrical energy is generated through offshore wind farms. This makes the UK a pioneer in energy decarbonization, decentralization, democratization, and digitalization. According to a report by National Grid in 2022, approximately 27% of UK electricity was generated by wind farms, accounting for more than 20 GW. Meanwhile, this number for the first three months of 2023 was about 32%, which is equal to 24 TWh of electric energy. The National Grid forecasts that by 2030, more than 50 GW will be produced by wind farms, while this number for 2050 would be up to 125 GW [18], [19]. In UK, there are six projects related to offshore wind farms, including Robin Rigg, Beatrice, Aberdeen Bay, Levenmouth, HyWind, and Kincardine. The Seagreen project uses 114 giant offshore turbines to generate approximately 1.1 GW of electrical power. As depicted in Figure 4, turbines are located 27 km off the Angus Coast in the North Sea's Firth of Forth, where the foundations of turbines are about 60 m under seawater. The output voltage of each turbine's transformer (140 transformers in one farm) is 66 kV, which can deliver 10 MW of power. At the same time, a 1.1 GW transmission transformer on the shore collects all electrical power from the turbines and transmits it to the main power system. Siemens is currently designing and manufacturing transformers of each turbine as well as the transmission transformer for the whole farm. Superconductivity could play a key role in reducing transformer size, weight, and losses and increasing the efficiency and reliability of delivered power. Fault current limitation and tolerance, extended overload endurance, and environmentally friendly nature of HTS transformers are promising solution for offshore wind farms, towards the delivery of safe and reliable electrical energy.

2. Advantages of HTS transformers over the conventional

The benefits of HTS transformers for use in power grids or transportation systems are explained as follows.

2.1. Total ownership cost

As seen in Table 1, the purchase price of superconducting tapes or wires is currently higher than copper wires. However, it is unfair to compare HTS transformers with conventional oil-immersed transformers solely on the initial purchase price. Total ownership cost (TOC) is a fair index to compare these two types of transformers. TOC is defined as the total cost of a transformer during its lifetime, including purchase and operating costs.

The TOC of an HTS transformer consists of the following components:

- Purchase price of the HTS transformer
- Purchase price of the required cooling system
- Re-injection of coolant fluid in the case of an open-loop cooling system
- Maintenance and testing of the transformer
- Maintenance of the cooling system
- Cost of no-load loss
- Cost of load loss
- Transportation and installation costs

On the other hand, the TOC of a conventional transformer consists of elements such as:

- Purchase price of the transformer
- Cost of changing the insulating oil

When HTS transformers face overload conditions, the temperature of HTS tape does not significantly increase, and a slight rise in temperature is suppressed and stabilized by the cryogenic cooling system

- Maintenance and testing cost of the transformer
- Cost of safety measures against fire hazards
- Cost of no-load loss
- Cost of load loss
- Transportation and installation costs

For a fair comparison between HTS and copper-based transformers, all components of TOC must be considered. However, values of these components depend on many factors, including apparent power, operating conditions, and load conditions. In HTS transformers, the highest cost is related to the purchasing cost and cooling system cost; besides the purchasing cost analysis of conventional transformers, an important cost is power loss consideration as. In this case, not only the power is dissipated in the copper transformer, but also the rise of temperature deteriorates insulation and causes aging. Although it may seem that the cost of conventional transformers is lower than the cost of HTS transformers, it should be mentioned that in the next 10 years, the cost of superconductors at about 220-230 US$/kA.m today for YBCO could be significantly reduced to around 50 US$/kA.m [3]; such a reduction in the cost of copper wires is not expected.

Generally, HTS transformers have about 20% lower TOC, 30% lower loss, and 45% lower weight, which makes them promising options for power grid planning and expansion [20]. Also, artificial intelligence (AI) methods can be used to make improvements in the fabrication of superconducting tapes and HTS transformers, making them more cost-competitive relative to conventional transformers [21].

2.2. Operation in overload conditions

When conventional transformers face overload conditions, the winding temperature and top oil temperature increase sharply. This degrades dielectrics and, consequently, reduces lifetime. However, this is not the case for HTS transformers. A well-known rule of thumb for conventional transformers states that the lifetime of conventional transformers is halved for an increase in insulation temperature of 10°C [22]. To minimize aging, a conventional transformer cannot usually operate at overload for more than a few minutes. Subsequently, the transformer is isolated from the power network. On the other hand, when HTS transformers face overload conditions, the temperature of HTS tape does not significantly increase (due to design considerations and HTS tape specifications). A slight rise in temperature is suppressed and stabilized effectively by the cryogenic cooling system. Therefore, overloads do not harm HTS windings or insulation. This is an extraordinary characteristic of HTS transformers, especially when installed in bulk power systems, where they can reduce the risk of failure, load shedding, and power system quality problems. If designed appropriately, HTS transformers may operate at 100% overload for many hours; conventional transformers can only tolerate partial overload for a few minutes.

2.3. Compact and lightweight

The size and weight of an HTS transformer are 45% to 50% lower than a conventional one [16], [23]. This is because HTS tapes have extremely low weight, density, and thickness relative to copper wires, while the former can carry much higher current density. Moreover, the compact structure and high current density of HTS tapes result in reduced dimensions of the transformer's core window. This renders HTS transformers an optimal solution for applications that require the smallest size and lightest weight. For instance, in transportation applications such as electric trains, size and weight must be minimized. This can be attained by HTS traction transformers. Highly populated urban areas that require a small footprint are another potential application for HTS transformers.

Installation of a new transformer unit incurs transportation costs. For larger MW-scale conventional transformers, costs can be expensive (up to hundreds of thousands of USD). The cost of transportation of HTS transformers can be 50% lower, given their smaller size and weight.

Fault tolerance and fault current limiting of HTS transformers are the most important features of power systems applications

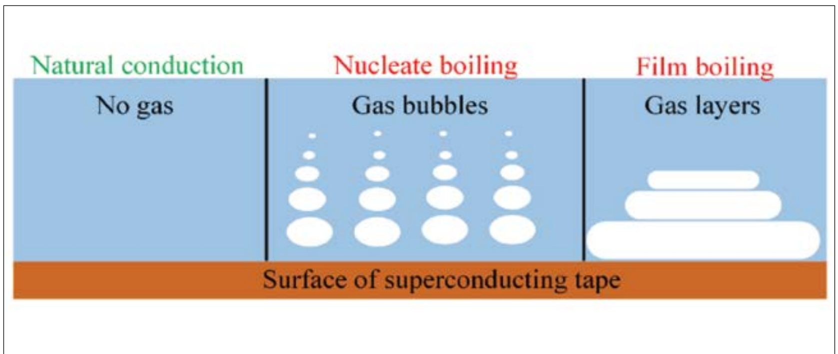

Figure 5. Pool boiling heat transfer regimes in LN_2

2.4. Fault tolerance and fault current limiting

Fault tolerance capability and fault current limiting of HTS transformers are the most important features of HTS transformers to be used in power systems applications. This is especially so for renewable wind energy systems, enabling decarbonized, decentralized, and digitalized energy production [24].

When the current abruptly increases due to short circuit faults, the temperature of HTS tapes increases. Because of this rise in temperature, they transition into a non-superconducting state. Consequently, the resistivity of superconductors increases dramatically to values much higher than conventional metals, near that of ceramics. As such, the fault current is suppressed in HTS transformers; in other words, they have "fault current limiting capability." This capability protects other devices connected to the transformer against fault currents. However, if a fault remains for a long time, such that the temperature of HTS tapes surpasses 400 K [25], the superconducting windings of a transformer may burn up. A new concept was introduced to avoid potential burnout and extend the fault withstand time of HTS transformers, known as a "fault-tolerant HTS transformer." Example methods for fabricating fault-tolerant current-limiting HTS transformers include [26]:

i) designing thicker superconducting tapes with thicker stabilizer layers to increase thermal mass,
ii) designing in tape materials with high resistivity, such as brass and stainless steel,
iii) reducing the base temperature to increase heat transfer during a fault,
iv) coating transformer windings with insulation.

Regarding the last case, when a fault occurs, more bubbles are generated on the winding surface. Bubbles facilitate the transfer of heat generated during a fault to the coolant fluid, increasing temperature less dramatically [10]. A simple schematic of heat transfer regimes in LN_2 is shown in Figure 5. Under the natural convection heat transfer regime, no gas bubbles are formed, and heat transfer is conducted by convection. With current (heat energy) increase, temperatures on tape surfaces increase, and gas bubbles appear in a cryogenic coolant fluid; thus, the nucleate boiling regime is initiated. Finally, if the surface temperature increases more, heat transfer enters the film boiling regime, where gas layers are formed around the tape surface, resulting in a rapid increase of superconductor temperatures [27].

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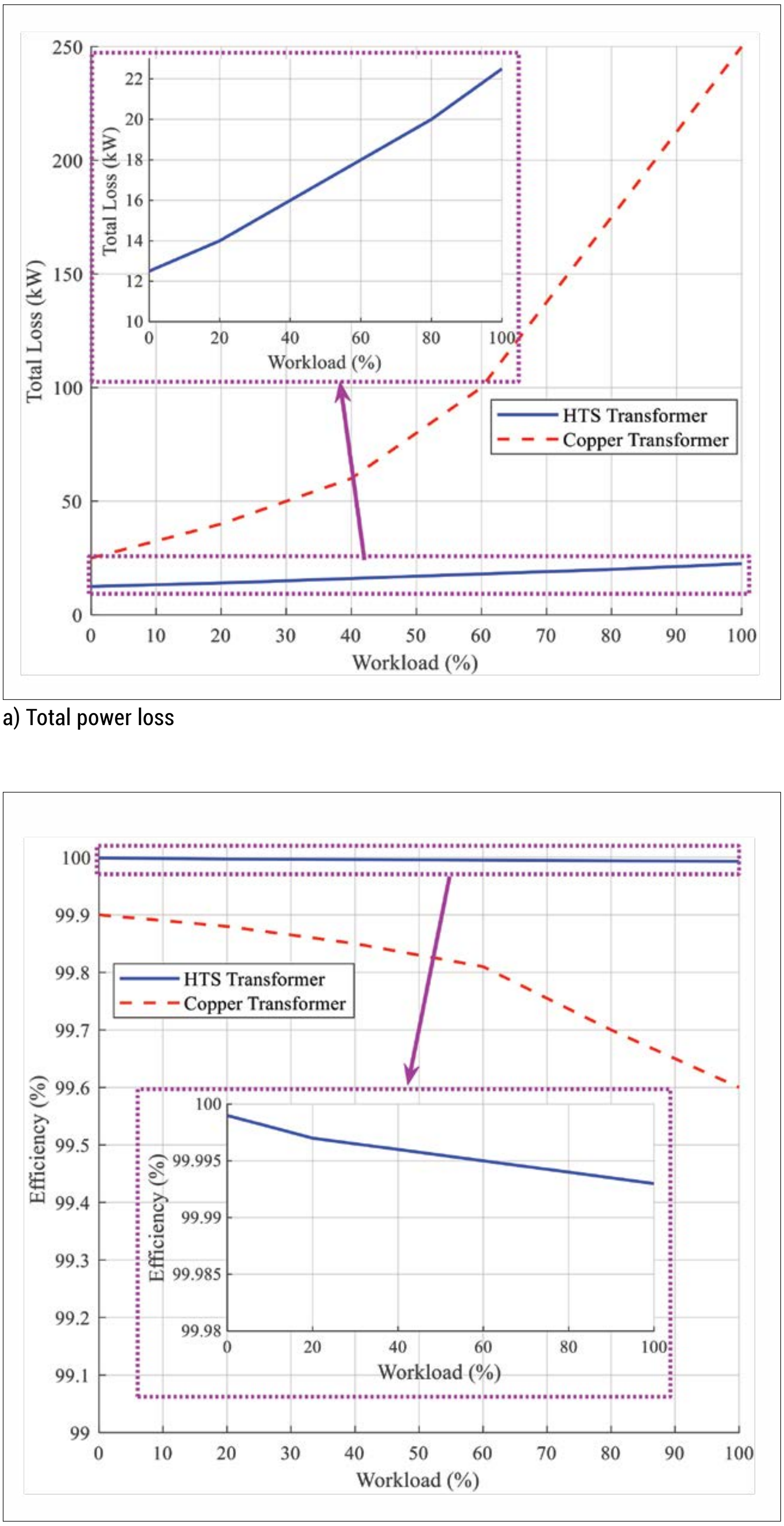

a) Total power loss

b) Efficiency

Figure 6. Performance of conventional and superconducting transformers rated 63 MVA, 50 Hz, 21/9.09 kV [30]

There is no insulating oil in HTS transformers, meaning that the possibility of oil fire hazards is completely eliminated

2.5. Eliminated risk of fire hazard

There is no insulating oil in HTS transformers, meaning that the possibility of oil fire hazards is eliminated. Further, LN_2 is non-toxic and does not harm the environment, unlike insulating oil in conventional transformers. Elimination of fire hazards is a property of HTS transformers, especially when used in sensitive industries that require the least possible risk of fire hazard, such as electric transportation. Conventional transformers incur a significant cost of installing fire suppression equipment, unlike HTS transformers. Such a cost for a larger MW-scale conventional transformer could be a few hundred thousand of US dollars. This could render HTS transformers more competitive economically.

2.6. Higher efficiency and reliability

Electromagnetic losses in HTS transformers consist of magnetization loss and transport current loss. The former is due to induced external magnetic fields, while the latter is related to passing current through HTS tape [28]. There are also other components of losses in HTS transformers, such as current lead loss, cryostat loss, and iron core loss [29]. These losses are much lower than the ohmic loss in conventional transformers and can be suppressed by proper design and operation procedures. Lower loss in HTS transformers results in higher efficiency and economic benefits compared to conventional transformers.

Two previously discussed properties of HTS transformers, fault tolerance, and overload performance, improve power system reliability compared to conventional transformers. Under such circumstances, requirements for redundant units in power systems in case of faults and failures are reduced. Also, under overload conditions, there is no need for backup transformers and extra protection units, as HTS transformers tolerate overloads for a long time. The reliability and efficiency of superconducting transformers will increase further by future improvements in cooling systems, the structure of HTS tapes, further R&D studies, industrial-scale production, and more funding. Figure 6 displays the total losses and efficiencies of HTS and copper transformers under different loads. The efficiency of a copper transformer at full load is reduced extensively due to high ohmic losses. In contrast, an HTS transformer has efficiency near 99.99% even at full load due to low total losses, including cryostat and cryocooler losses. It should be noted that the copper transformer has an annual energy loss of 839.7 MWh, while the respective value for the HTS transformer is 160.3 MWh. For copper-based transformers, 75% of energy loss relates to winding losses, while 25% is related to iron core losses. For HTS transformers, 67% is related to iron core losses and only 12% to windings; the remaining losses are related to cryostat and current leads [30].

An HTS transformer has efficiency near 99.99% even at full load due to low total losses, including cryostat and cryocooler losses

3. Promising applications of HTS transformers: future trends

3.1. Fault-tolerant HTS transformers

Fault-tolerant HTS transformers (FTHTST) are capable of tolerating fault current for many cycles by limiting fault current to reduce the risk of failure. Their performance is highly dependent on the structure of HTS tapes, the properties of insulation [31], and the grid parameters [32, 33]. Implementation of FTHTSTs is advantageous in power systems with high level of renewable energy resources, such as wind farms. In the presence of such units, potential fault current level increases. Thus, the application of FTHTSTs can improve grid reliability. Fault current limiting of FTHTSTs increases safety. Fault tolerance improves reliability indices, and loads can be supplied without interruption [27].

To gain a better understanding of the economic and technical benefits offered by FTHTST, Figure 8 is presented. Figure 7(a) shows the common practice of using conventional transformers, fault current limiters, and circuit breakers to connect a wind farm to the grid. Under such an arrangement, if a short circuit occurs in the system, the fault current limiter will limit the first peak of the fault, but usually, the transformer needs to be isolated to protect the turbine; however, this isolation compromises the stability of the power system. Another problem is that both the transformer and fault current limiter are conventional: in steady-state operation, they have high ohmic losses even when no significant power is delivered by the turbine.

If an HTS transformer replaces the conventional one, as shown in Figure 7(b), the transformer impedance and losses are reduced, but grid stability is still compromised. Higher grid stability and reliability can be obtained using a superconducting fault current limiter (SFCL) in series with the secondary side of the HTS transformer, as shown in Figure 7(c). However, this increases the cost and cooling power significantly, although the rating of the circuit breaker to protect the wind farm can be reduced. Finally, FTHTST replaces the conventional transformer and fault current limiter, as shown in Figure 9(d). This increases the stability and reliability of the grid; circuit breaker ratings are also reduced, resulting in total cost decrease.

Stability issues originating in wind turbine isolation can be handled by an SFCL and an HTS transformer. However, managing, monitoring, designing, and protecting two cooling systems (one for SFCL and one for the HTS transformer) is complicated and expensive. On the other hand, stakeholders, engineers, designers, system operators, and transmission and distribution companies can obtain lower cost and high power grid reliability for power systems connected to wind farms by taking advantage of FTHTSTs. Note that the grid structure of Figure 7(d) is not only fault-limited and fault-tolerated but also reduces the risk of load shedding and other blackouts.

Implementation of FTHTSTs is advantageous in power systems with high penetration levels of renewable energy resources, such as wind farms

3.2. HTS transformers in transportation systems

HTS transformers can also be used in cryo-electric transportation systems, especially electric trains. This is due to their low weight and size, which make HTS traction transformers an ideal solution. Also, the low risk of fire hazards in HTS transformers is an advantage over conventional transformers [13]. This reduces health and safety risks to passengers and, thus, increases system reliability. One of the most important projects for HTS traction transformers is in Chinese high-speed trains with single phase, 6.6 MVA apparent power, less than 3 tons, more than 99.5% efficient, 43% short circuit impedance, and 25/1.9 kV voltage [34]. There are other projects using traction transformers as well, such as one transformer rated 1 MVA, 25/1.4 kV in Germany [35], and another rated 4 MVA, 25/1.2 kV in Japan [36].

3.3. HTS transformers in data centres, charging station, and battery/energy storage applications

Recently some investigations were conducted to implement HTS cables (both DC and AC) in data centers. By having such cables, as they require a cryogenic cooling system, there is also room for implementing the MVA-scale HTS transformers in both single-phase and three-phase structures in data centers to connect the data center to the main power system. They can be used as voltage conversion units and protection systems. However, there is a need for further improvements and R&D to make HTS transformers commercially available for data centers.

In addition, power transformers are used for different sectors that accounted as auxiliary services for power systems. The first type is a step-down power transformer in charging stations of the electric vehicles. These types are usually used to connect the high voltage power system to the charging station with low voltage characteristic. Usually, this type converts the voltage level of secondary distribution systems e.g., 10 kV or more to lower voltages such as 480 V or 240 V that is more appropriate for charging station applications. Usually, they are categorized into three subgroups, the transformers for low-power charging stations that requires 3 kW to 22 kW power, the transformers for medium-power charging stations with a power range of 22 kW to 150 kW, and finally, fast, and high-power charging stations which have power range of 150 kW to 350 kW [37].

Second auxiliary application of power transformers is related to integration of

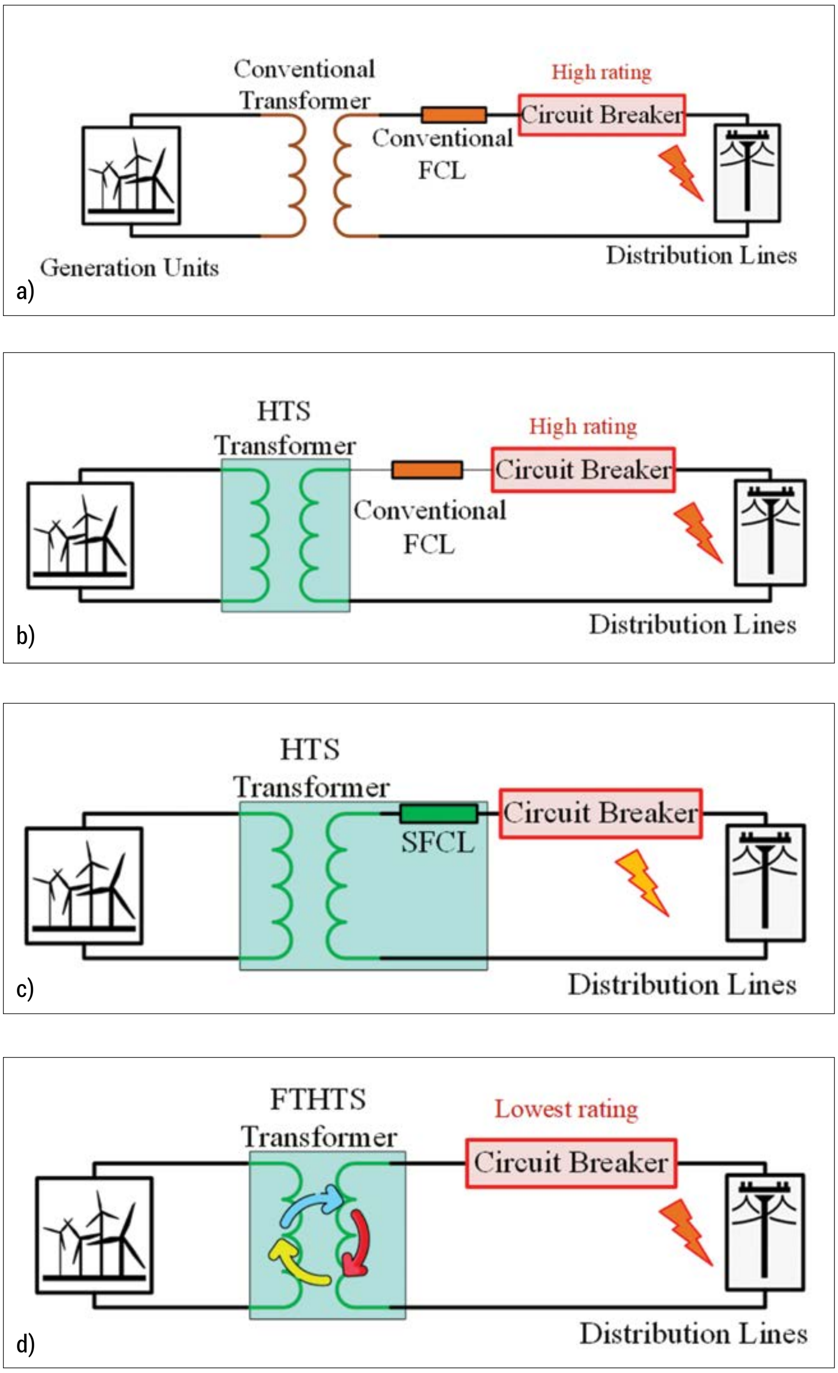

Figure 7. Different structures of power systems with wind farms in the presence of conventional or HTS transformers

HTS transformers can also be used in cryo-electric transportation systems, especially trains, thanks to their low weight and size, which make HTS traction transformers an ideal solution

the energy storage units such as large battery arrays into the power systems. Regarding the voltage level of the grid and nominal voltage of the energy storage unit, these transformers could be step-down type or step-up type. These types of transformers for battery applications could be categorized in three subgroups which are low voltage, medium voltage, and high voltage. The low voltage class usually has the nominal voltage up to 1 kV and the power range is between 10 kW to 1000 kW. This class is used for low power, low voltage, and small-scale energy storages that are mostly used in nanogrids, microgrids, and residential purposes. The medium voltage class has the voltage of 1 kV to 69 kV while the power ranges from 1 MW to 10 MW. Usually, this class is used for medium-scale energy storage units that could be found in industrial applications. Finally, the high voltage class has voltage range of 69 kV to 230 kV with a power ranging from 10 MW to 100 MW. The high voltage types are used for large-scale battery and energy storage units which aim to increase the stability, availability, and reliability of transmission systems [38].

With respect to the power range of the above transformers, HTS transformers could replace the conventional types of charging station. Since, the electrification of vehicles is a growing interest, the required power by charging stations will increase to MW range. At this stage, HTS transformers could play their crucial role for charging station applications with respect to their fault tolerability, overloading resistivity, and low sizes. Also, with respect to the growing penetration level of the renewable energy resources, HTS transformers could be also used in large-scale energy storage devices. Since, these types has high power and high voltage characteristic, HTS transformer could replace the conventional types, since they have lower weight, lower loss, and high reliability.

3.4. Mobile transformers

HTS mobile transformers (HTSMT) are another potential application for HTS transformers, unlocked by low weight and high-power density. Usually, conventional mobile transformers offer 2.5 MVA to 60 MVA power at voltages higher than 230 kV. HTS transformers could increase power ratings above 60 MVA [39]. A 1 MVA demonstrator HTSMT was built in 2001. The transformer operated at 67 K to convert 25 kV to 1.4 kV at an efficiency of 97.75% [40]. An attractive application for HTSM transformers is peak shaving for the sake of demand response. This increases power quality, grid capacity, reliability, stability, and resiliency and reduces the risk of load shedding. Also, HTSMTs are used when one of the main HTS transformers needs to be repaired or replaced.

3.5. Smart HTS transformers

As reported in [41], transformers play a more important role in future smart grids than merely as voltage conversion units. By integrating intelligent electronic devices, smart power transformers could also be used as data collection and communication points. This is a great opportunity to use smart HTS transformers in smart grids and smart cities. HTS transformers are an ideal choice primarily because of their compact size and low weight, as required in most smart grids. Also, resistive loss of electronic devices is minimized, and efficiency is improved by the implementation of sensors and data-gathering devices at or near cryogenic temperatures. This can improve data quality and avoid the risk of bad data, which is especially pernicious in smart cities.

4. Summary

High-temperature superconducting (HTS) transformers are a killer technology that offers technical advantages over conventional transformers, such as higher power density, lower weight, and smaller size. Fault tolerance, overload capability, and high reliability make HTS transformers an excellent choice for future power systems and microgrids. In addition to the advantages above, reduced fire hazard risk offers add value to electrified transportation units such as high-speed trains. Fault Tolerant HTS (FTHTS) transformers can play a key role in future power systems, especially those connected to wind farms and other intermittent renewable energy resources. As the latter increases penetration levels in power systems, not only is the risk of fault currents increased, but also their amplitude. Accordingly, FTHTS transformers are particularly pragmatic and can increase electrical grid protection.

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High-temperature superconducting (HTS) transformers are a killer technology that offers technical advantages over conventional transformers, such as high-power density, lower weight, and smaller size

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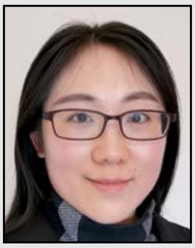

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