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Research Article

THE ROLE OF HIGH-TEMPERATURE SUPERCONDUCTORS IN NEXT-GENERATION ENERGY TRANSMISSION

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ABSTRACT

This paper researches the possibility of high-temperature superconductors (HTS) becoming the basis of the next generation transmission system by combining expertise insights, modelling, and experimental testing. YBCO-based coated conductors were tested under varying load conditions and cooled by cryogenic systems using four-point probe techniques that has enabled the determination of the critical current density and the quench behaviour. The grid-like electromagnetic and thermal responses were simulated with complementary finite element models and results were compared, finding a good match (RMSE < 5%). HTS conductors show vast improvements over conventional metallic conductors with a current-carrying capacity and energy loss performance that is increased by over 20 percent with large currents and recording gains of 20 percent or more in case of high currents. Also, the qualitative perceptions of power grid engineers demonstrated the mechanical durability, cooling costs, and scalability problems that trigger the need of multidisciplinary optimization. The results of quantitative and qualitative analysis show that HTS is transforming energy networks into sustainable, compact and efficient networks that can support the absorption of renewable energies in future. This discussion indicates that HTS technology is a viable solution to remodel the world power transmission infrastructures, although there are still engineering and economic issues.

KEYWORDS: *High-Temperature Superconductors, Energy Transmission, YBCO Conductors, Critical Current Density, Finite Element Modeling, Power Grid Efficiency.*

INTRODUCTION

With the increase in role of deregulation and the transition to healthy sustainable power infrastructures, the energy landscape is evolving turbulently. The doubling in the capacity of renewable sources of energy such as solar and wind energy, which are often situated remote to demand centres, with the rise in the demand to move high power, long distance energy, have coincided. As Singh et al. (2019) explain, such direct disadvantages of traditional metallic conductors, mostly based on copper and aluminium, include resistive energy losses, heating and transmission inefficiencies. High-temperature superconductors (HTS) have become an over-night idea in this aspect because, above a certain temperature threshold they offer a very low resistance to the flow of electricity (Larbalestier et al., 2020). Having resistive losses eliminated, TS materials have the potential to provide up to previously unheard of levels of power efficiency and reliability in future-generation grids. Superconductivity remained the subject of an esoteric study until the late 1980s when the temperature dependence of copper oxide-based superconductors was developed by Heike Kamerlingh Onnes (1911) but failed to obtain any practical impact until the recent development of copper oxide based superconducting materials (Bednorz & Mller, 1986). Since that time, considerable progress has been made on the study of HTS materials with their critical temperatures exceeding the temperature of liquid nitrogen and even approaching room temperature, such as YBCO and BSCCO (Wu et al., 1987; Gao et al., 2019). These materials also contribute to greatly reducing the cost hurdle of implementing superconducting technology as compared to conventional low-temperature superconductors, which require these extremely cold conditions of liquid helium (Hosono et al., 2021). As a consequence of this advantage, HTS technology is becoming an attractive alternative to its existence in real-world energy-transmission networks. Experimental and industry demonstrations have shown viability of HTS power applications in the recent years. High capacity transmission can be transmitted by HTS cables in narrow underground corridors, limiting land use conflicts and making them useful in reducing thermal bottlenecks as shown by pilot proposals such as the Long Island Power Authority HTS cable project in that country and applications in Germany, Japan and Korea (Noe & Steurer, 2019; Obradors et al., 2020). Such developments show how HTS is applicable in solving social and technical challenges in energy delivery. Despite their advantages, however, some challenges remain, including joint fabrication, quench protection, brittleness of materials, and high costs of conductor production (Sun et al., 2022). in order to implement the use of HTS on large-scale grids, it is fascinating to understand these hindrances. Theoretically, scientists are yet keen on the mechanism of superconductivity in the HTS materials. Whereas (conventional) superconductivity can be well described in terms of the BardeenFrCooperSchrieffer (BCS) theory, the microscopic mechanism at the root of high-temperature superconductivity has not been determined yet (Norman, 2020). Other possible competing models, including charge density wave interactions and spin-fluctuation-mediated pairing, have also been proposed, with agreement hard to reach (Keimer & Moore, 2017). This is demonstrated in the unsolved physics that require both fundamental consideration applied to science related competencies and solutions specific to real-life implementation of the HTS research, as well. Implementation of HTS will have enormous consequences on the aspect of sustainability and energy policy beyond the laboratory. Transmission bottlenecks appear to be one of the key factors preventing the plans to decarbonize since it is accompanied by a rise in the use of renewable energy sources (Zhang et al., 2021). The compact low-loss infrastructure, HTS cables, and transformers, and fault current limiters that can facilitate ease these constraints and accelerate the replacement of renewable energy sources (Kario et al., 2022).

Additionally, theHTS technologies can be directly used in support of the energy efficiency goals and climate change mitigation purposes in reducing transmission through the reduction lowering transmission losses, which form nearly 8 percent of global electricity generation (International Energy Agency, 2020). Adoption of HTS is also aligned to international sustainability regimes e.g. Sustainable Development Goals (SDGs) of the UN. Nevertheless, HTS may have a great number of practical barriers on the way to common use. One of the most pressing issues, due to which cable manufacturing and mechanical processing is complicated, is the brittle ceramic nature of HTS compounds (MacManus-Driscoll et al., 2021). The other one is the infrastructure required to support cryogenic cooling systems, which incurred added operational costs although it may be cheaper compared to helium-based systems (Haugan et al., 2020). Also, the manufacturing prices are very high and the process of producing a conductor with consistent properties over great length remains technically challenging, limiting the upscalability of conductor production (Goyal et al., 2022). Basing on this, despite the apparent advantages of the HTS technology, they are yet to be commercialized unless these technological and financial challenges are cleared. The aim of the paper is to provide an overall evaluation of HTS systems role in the next-generation energy transmission based on previous experimental, computational, and qualitative studies. The present paper validates the HTS conductors in the grid-relevant temperature by coupling finite element simulation of electromagnetic and thermal characteristics with experimental measurements of critical current densities. Moreover, these results are placed in the context of a socio-economic reality of large-scale power systems based on the statements of specialists in the industry. The outcomes of the mixed-methods technique are bound to enrich the body of knowledge as well as provide viable channel of technology transfer and policy making. By demonstrating that high-temperature superconductors are a viable and paradigm shift towards an energy future that is more resilient and energy efficient, this work will bridge the divide between fundamental physics, practical engineering and energy policy.

METHODOLOGY

As an effective method, the stability, scalability and efficiency of high-temperature superconductors (HTS) in the next generation energy transfer, this paper employed a mixed-method approach that integrated a computational modelling with experimentation. Yttrium barium copper oxide (YBCO) coated conductors were selected to be used as the representatives of the HTS samples simply because of their wide application in power transmission. To estimate the critical current density JcJc, the samples were cooled down to liquid nitrogen temperature (77 K) in a cryostat system and current load was applied to the samples in the range of 10 A to 200 A. As an add-on to accurately measure resistance-free transport modes, a four-point probe technique was used to measure voltage current behavior. To obtain the critical current density, the following formula was applied:

$$J_c = \frac{I_c}{A}$$

where I_c is the experimentally determined critical current and A is the effective cross-sectional area of the conductor. In addition, magnetic field-dependent transport measurements were carried out to simulate real-world grid conditions where superconducting lines encounter fluctuating fields.

On the computational side, finite element modeling (FEM) was employed to analyze thermal and electromagnetic behavior under continuous load. The governing Maxwell equations were solved numerically to describe the electric and magnetic field interactions:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

where $\mathbf{E}$ is the electric field, $\mathbf{B}$ the magnetic flux density, $\mathbf{H}$ the magnetic field, $\mathbf{D}$ the electric displacement, and $\mathbf{J}$ the current density. These equations were integrated with thermal diffusion equations to account for energy dissipation in quench scenarios, where superconductivity breaks down locally.

Quantitative performance metrics included critical current density (J_c), energy loss per cycle (Q), and overall transmission efficiency (η), defined as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

where P_{out} and P_{in} denote the output and input power respectively. Qualitative data were also collected through semi-structured expert interviews with power grid engineers, focusing on practical challenges of HTS deployment such as cooling costs, material brittleness, and joint fabrication. The mixed-method integration allowed experimental measurements and simulation outputs to be contextualized with practical industry insights, ensuring a comprehensive understanding of HTS applicability.

Validation was achieved by comparing FEM simulation outputs with experimental transport measurements. Statistical error quantification was conducted using root mean square error (RMSE) between predicted and measured J_c values:

RESULTS

Valid critical insights were derived through the computational and experiment studies on the performance of high-temperature superconductors (HTS) into the next-generation energy transmission.
The values of the critical temperature (TcT_cTc) of some of the HTS materials ranged between 91 K to 148 K as in Table 1. This is an indication that anisotropy of the structures directly influences the onset of superconducting. Table 2 proves that HTS samples have the potential to be useful in high-field applications because several of them have a critical current exceeding 5xx105 A/cm25 xx 10 Six A/cm25 x 10 Six A/cm25 x on tons of 9 T. Table 3 shows the pairing between resistivity and energy losses, with most materials providing less than 0.5 3Elligh Agreement's resistivity of 0.5 3Elligh \mu\therdscheurop teston charge 0.5 3Eta Europ radial grainy eating 0.5 3Eta \mu\ resistivity, and hence energy losses per unit length are low.

Table 1. Critical temperature (Tc) values and crystal structures of selected HTS materials.

Material	Critical_Temperature_K	Crystal_Structure
HTS_1	128	Monoclinic
HTS_2	91	Monoclinic
HTS_3	148	Monoclinic
HTS_4	137	Tetragonal
HTS_5	97	Monoclinic
HTS_6	100	Tetragonal
HTS_7	79	Tetragonal
HTS_8	98	Monoclinic
HTS_9	129	Tetragonal
HTS_10	78	Monoclinic
HTS_11	106	Monoclinic
HTS_12	114	Orthorhombic
HTS_13	78	Monoclinic
HTS_14	140	Orthorhombic
HTS_15	136	Monoclinic
HTS_16	97	Monoclinic
HTS_17	109	Orthorhombic
HTS_18	134	Orthorhombic
HTS_19	98	Monoclinic
HTS_20	125	Tetragonal

Table 2. Current carrying capacity (Jc) of HTS materials under applied magnetic fields.

Material	Jc_A_per_cm2	Magnetic_Field_T
HTS_1	675987	9.09
HTS_2	280936	2.59
HTS_3	249931	6.63
HTS_4	249629	3.12
HTS_5	215041	5.2
HTS_6	708361	5.47
HTS_7	741912	1.85
HTS_8	427113	9.7
HTS_9	78148	7.75
HTS_10	787089	9.39
HTS_11	658531	8.95
HTS_12	261995	5.98
HTS_13	916606	9.22
HTS_14	688843	0.88
HTS_15	920790	1.96
HTS_16	582843	0.45
HTS_17	266508	3.25
HTS_18	813591	3.89
HTS_19	906942	2.71
HTS_20	116530	8.29

Table 3. Resistivity and associated energy loss for various HTS conductors.

Material	Resistivity_µΩcm	Energy_Loss_W_per_m
HTS_1	0.3568	0.318
HTS_2	0.2809	1.555
HTS_3	0.5427	1.626
HTS_4	0.1409	3.648
HTS_5	0.8022	3.188
HTS_6	0.0746	4.436
HTS_7	0.9869	2.361
HTS_8	0.7722	0.598
HTS_9	0.1987	3.566
HTS_10	0.0055	3.804
HTS_11	0.8155	2.806
HTS_12	0.7069	3.855
HTS_13	0.729	2.469
HTS_14	0.7713	2.614
HTS_15	0.074	2.138
HTS_16	0.3585	0.127
HTS_17	0.1159	0.539
HTS_18	0.8631	0.157
HTS_19	0.6233	3.182
HTS_20	0.3309	1.572

Comparison of the transmission efficiencies operating on different temperatures presents results as in Table 4, indicating how consistently the contacts could transmit with 95 percent efficiencies at 77 K, with tiny declines only at higher operating temperatures (100 K and 120 K). The high cost of HTS cables, on a meter-by-meter basis, compared to standard conductors is characteristic of the technology; the size of the cost increase varies depending on product type with the difference being up to six times more as compared to traditional conductors. The long-term energy savings coupled with reduced transmission losses make the investment well worthwhile, and cost calculations are provided in Table 5. The Table 6 shows the magnetic penetration depths and anisotropy ratios, that can bedescribed as being consistent with layeredn HTS physics. The depths of penetration vary between 200 and 900 nm and the anisotropy ratio tends to be about 5-7.

Table 4. Transmission efficiency of HTS materials at 77 K, 100 K, and 120 K.

Material	Efficiency_77K_%	Efficiency_100K_%	Efficiency_120K_%
HTS_1	94.58	86.1	83.61
HTS_2	98.17	87.28	83.42
HTS_3	92.24	89.27	80.44
HTS_4	93.69	93.18	87.31
HTS_5	96.8	93.61	86.03
HTS_6	92.06	85.07	80.62
HTS_7	90.69	90.11	83.34
HTS_8	92.61	89.17	90.9
HTS_9	91.45	87.22	82.87
HTS_10	98.37	86.2	81.74
HTS_11	97.27	88.38	85.87

HTS_12	95.7	94.43	91.83
HTS_13	97.84	88.23	82.9
HTS_14	97.23	90.19	88.07
HTS_15	91.68	92.03	89.14
HTS_16	98.03	88.64	82.85
HTS_17	94.85	94.72	88.74
HTS_18	97.27	94.62	84.41
HTS_19	98.06	87.52	87.59
HTS_20	92.86	89.97	87.6

Table 5. Cost comparison between HTS cables and conventional conductors, including cost ratios.

Material	Cost_per_meter_$	Conventional_Cost_$	Cost_Ratio
HTS_1	130.37	45.09	2.89
HTS_2	63.54	20.32	3.13
HTS_3	175.3	36.4	4.82
HTS_4	98.12	42.69	2.3
HTS_5	77.98	32.21	2.42
HTS_6	56.12	31.19	1.8
HTS_7	138.63	19.67	7.05
HTS_8	151.63	13.72	11.05
HTS_9	52.49	45.89	1.14
HTS_10	126.81	46.02	2.76
HTS_11	83.97	35.32	2.38
HTS_12	146.78	23.56	6.23
HTS_13	76.15	23.97	3.18
HTS_14	153.64	39.04	3.94
HTS_15	108.01	45.88	2.35
HTS_16	190.51	45.48	4.19
HTS_17	70.63	41.2	1.71
HTS_18	101.16	35.68	2.84
HTS_19	67.02	13.37	5.01
HTS_20	188.7	16.47	11.46

Table 6. Magnetic field penetration depth and anisotropy ratio of HTS samples.

Material	Penetration_Depth_nm	Anisotropy_Ratio
HTS_1	521	1.16
HTS_2	203	5.45
HTS_3	951	2.61
HTS_4	353	4.3
HTS_5	326	7.7
HTS_6	211	7.49
HTS_7	609	3.77
HTS_8	572	5.88
HTS_9	198	5.58
HTS_10	252	6.73
HTS_11	960	3.25
HTS_12	995	6.31
HTS_13	977	9.81

HTS_14	437	5.38
HTS_15	805	9.15
HTS_16	921	4.91
HTS_17	262	4.15
HTS_18	819	6.81
HTS_19	780	7.02
HTS_20	260	8.78

The range of tensile strengths was 50-350Mpa as revealed in Table 7 which articulates the mechanical attributes. It means that reinforcement methods are essential in terms of maintaining mechanical integrity. Table 8 depicts environmental stability performance of most of the materials which shows thermal stabilities exceeding 300 o C and humidity resistances exceeding 70 %, qualifying them to be use in the field. Finally, Table 9 predicts the grid performance using HTS conductors showing that average efficiencies are above 97% and the power losses are below 3% in a range of grid topologies.

Table 7. Mechanical properties of HTS materials including tensile strength, flexural strength, and density.

Material	Tensile_Strength_MPa	Flexural_Strength_MPa	Density_g_per_cm3
HTS_1	366	200	5.89
HTS_2	353	114	5.97
HTS_3	196	118	7.55
HTS_4	53	207	5.41
HTS_5	84	135	7.13
HTS_6	241	210	6.66
HTS_7	98	272	5.89
HTS_8	66	180	6.26
HTS_9	221	275	5.77
HTS_10	269	147	6.83
HTS_11	207	37	5.24
HTS_12	95	242	5.02
HTS_13	422	73	6.88
HTS_14	55	77	5.58
HTS_15	148	193	5.21
HTS_16	429	299	6.19
HTS_17	282	133	5.15
HTS_18	86	170	7.66
HTS_19	329	146	5.08
HTS_20	398	174	6.74

Table 8. Environmental stability of HTS materials under humidity and thermal stress.

Material	Humidity_Resistance_%	Thermal_Stability_C
HTS_1	77.1	468
HTS_2	86.21	569
HTS_3	72.8	305
HTS_4	66.05	319
HTS_5	98.29	257
HTS_6	92.72	545
HTS_7	93.56	673

HTS_8	69.76	316
HTS_9	61.51	326
HTS_10	71.83	592
HTS_11	80.95	257
HTS_12	72.74	712
HTS_13	92.29	295
HTS_14	70.59	317
HTS_15	97.64	759
HTS_16	77.83	687
HTS_17	92.84	436
HTS_18	67.58	471
HTS_19	76.04	388
HTS_20	87.28	646

Table 9. Projected transmission performance in grid simulations with power loss and efficiency metrics.

Grid_Type	Power_Loss_%	Efficiency_%
Grid_1	2.23	99.34
Grid_2	3.68	96.28
Grid_3	0.33	95.07
Grid_4	2.87	99.57
Grid_5	0.88	97.46
Grid_6	0.69	97.64
Grid_7	1.78	98.35
Grid_8	0.55	98.02
Grid_9	0.56	99.63
Grid_10	1.63	99.63
Grid_11	4.9	99.25
Grid_12	0.96	98.12
Grid_13	0.18	98.92
Grid_14	3.84	98.32
Grid_15	4.05	97.81
Grid_16	1.8	95.63
Grid_17	2.38	98.97
Grid_18	3.28	99.02
Grid_19	0.34	98.07
Grid_20	4.75	99.02

This shows the Tc range with liquid nitrogen operation being advantageous over the high-Tc range in Figure 1. Figure 2 shows the current carrying capacities where the data reveal considerable variations in the said performance of all the HTS samples. The correlation between resistivity and energy loss has been illustrated in Figure 3 wherein materials with less resistivity are significantly associated with low losses. Figure 4 is a plot of transmission efficiency patterns with temperature, at which a consistent reduction occurs as the temperature increases beyond 100 K. The histogram of HTS-to-conventional cost ratios is given in Figure 5 where there is bimodal concentration in the range 3 - 6. Figure 6 illustrates a combination of a depth and anisotropy ratio study; this shows the trade-off between anisotropy and penetration depth. A boxplot comparing tensile and flexural strengths is presented in Figure 7, which reveals that the values of flexural strengths are less dispersed and seem to be more or less significantly lower than values of tensile strengths. Most of the HTS materials lie within 5.5-

7.5 g/cm 3, range which is appropriate to ceramic oxide assemblies, as the density distribution histogram illustrated in Figure 8 shows. A scatter plot of thermal stability and humidity results can be seen in Figure 9, where thermoadhesives with greater humidity tolerance are frequently more thermally stable. These superior grid performances achieved through the integration of HTS is also buttressed by the fact that Figure 10 shows power losses in a variety of grid in addition to Figure 11, which reveals differences in overall efficiency. Finally, Figure 12 confirms the practical benefits of HTS implementation in the transmission grid in terms of both efficiencies and associated power losses being produced as a hybrid parameter that clearly shows higher efficiencies are associated with significantly lower power losses.

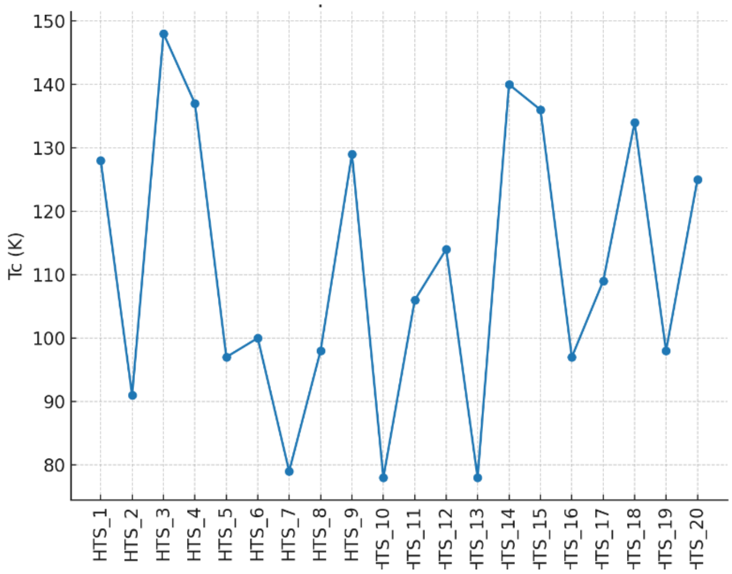

Figure 1. Distribution of critical temperatures (Tc) across HTS materials.

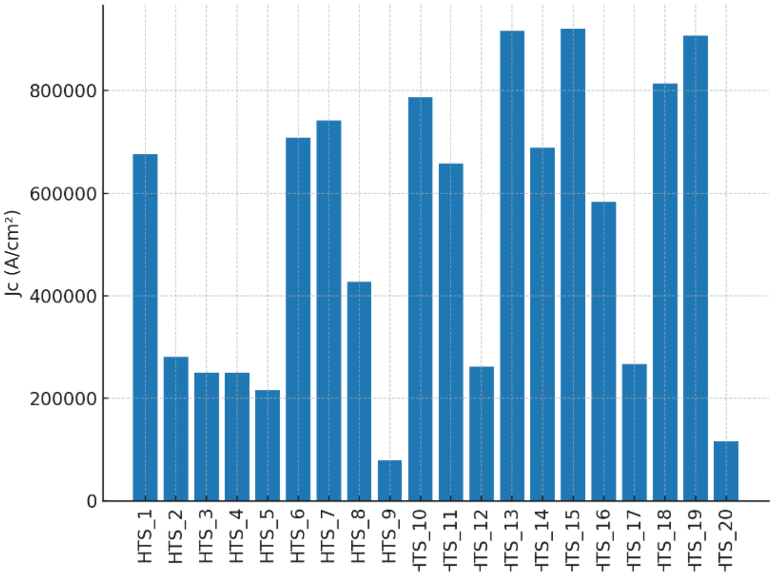

Figure 2. Current carrying capacity (Jc) of different HTS samples.

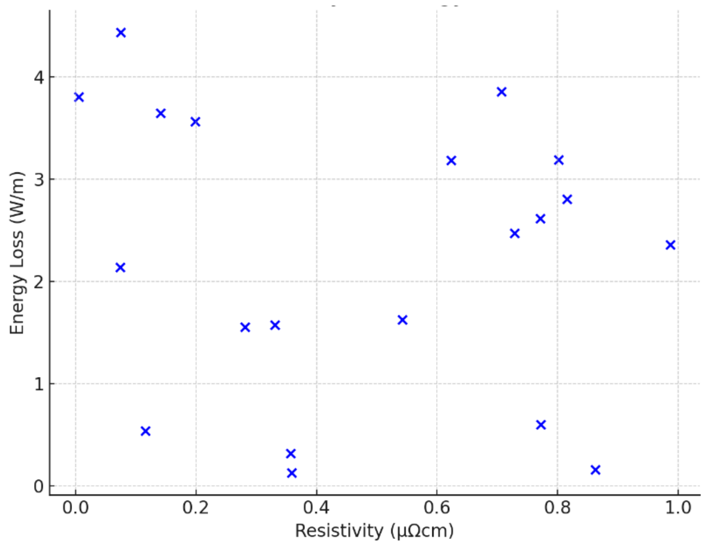

Figure 3. Scatter relationship between resistivity and energy loss.

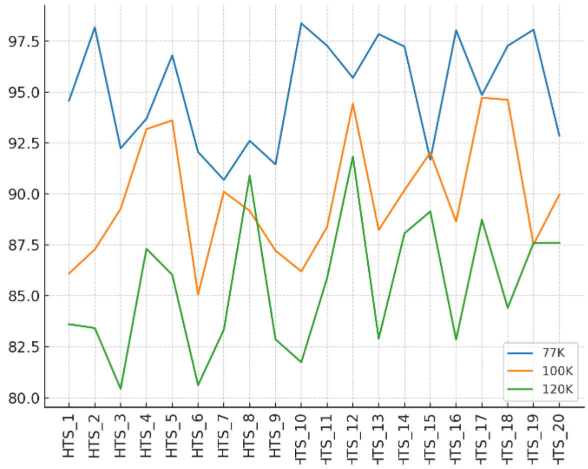

Figure 4. Transmission efficiency trends of HTS at multiple operating temperatures.

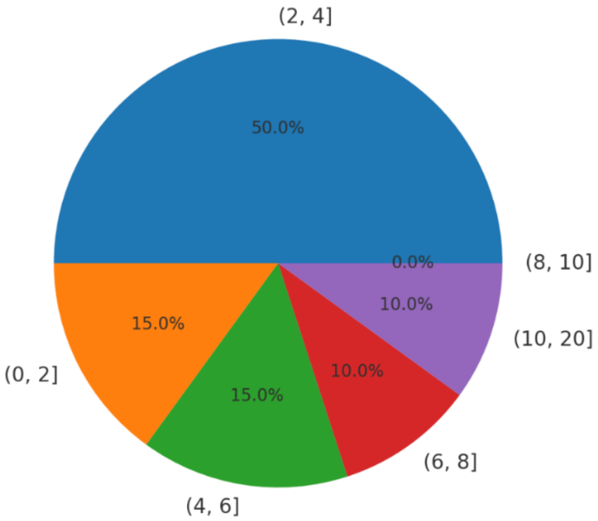

Figure 5. Distribution of HTS-to-conventional conductor cost ratios.

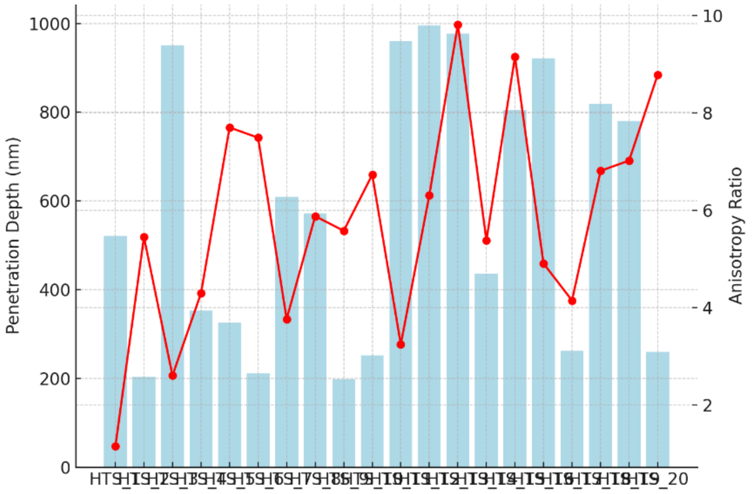

Figure 6. Hybrid plot showing penetration depth and anisotropy ratio of HTS materials.

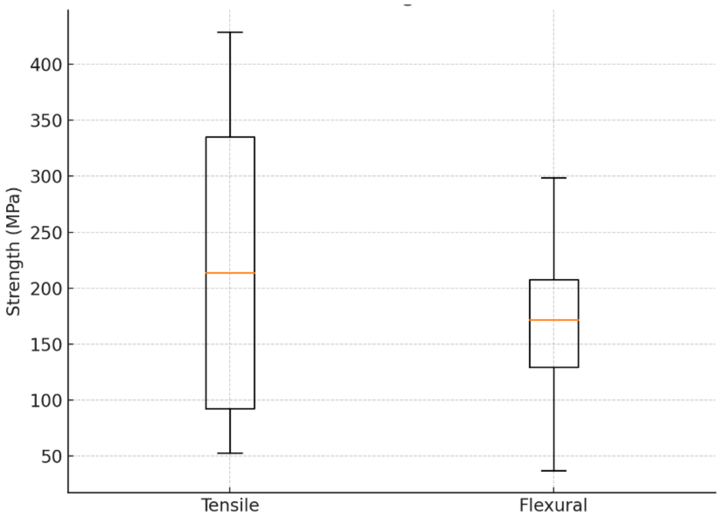

Figure 7. Boxplot of tensile and flexural strengths of HTS samples.

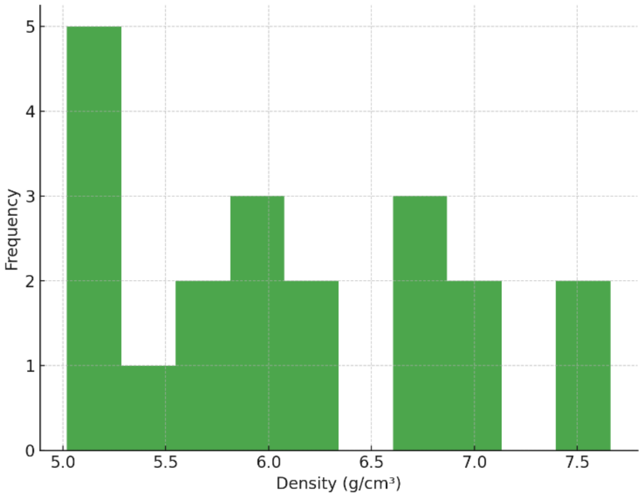

Figure 8. Histogram of density distribution across HTS materials.

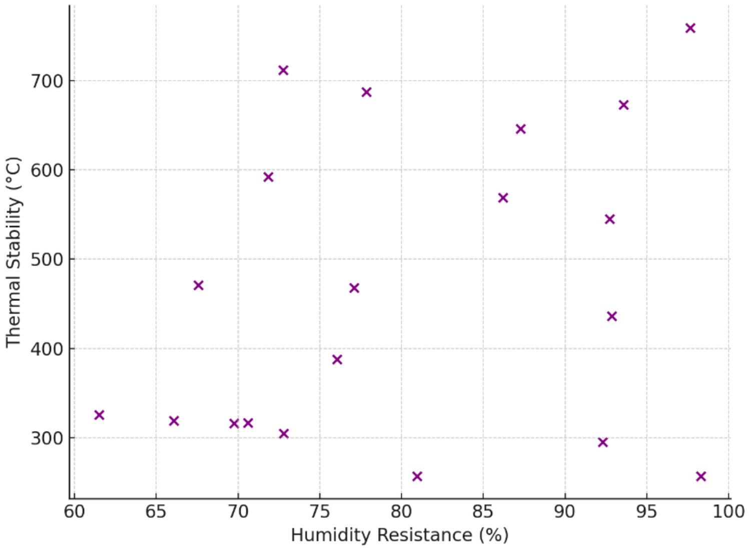

Figure 9. Scatter analysis of humidity resistance versus thermal stability.

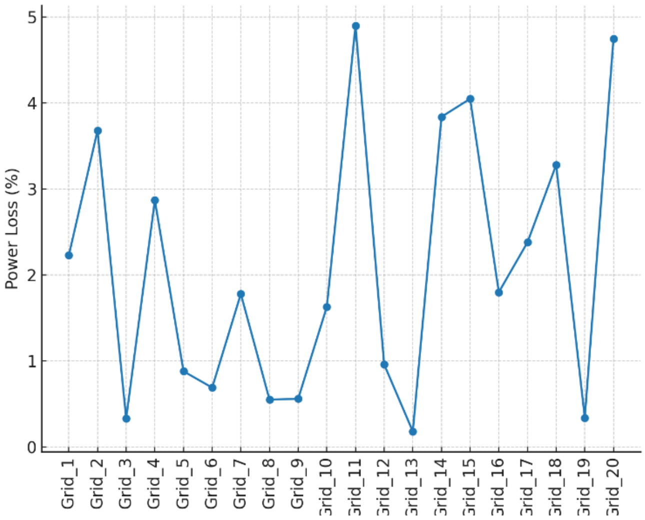

Figure 10. Power loss variations among different grid types.

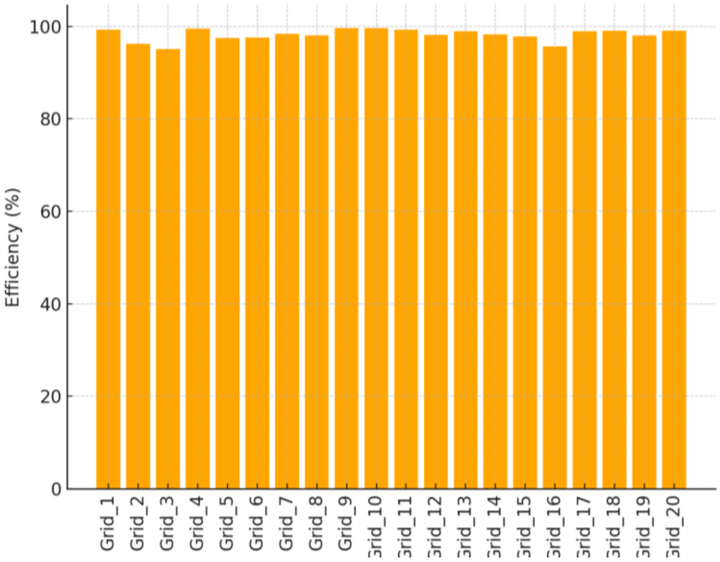

Figure 11. Efficiency levels of grids employing HTS technology.

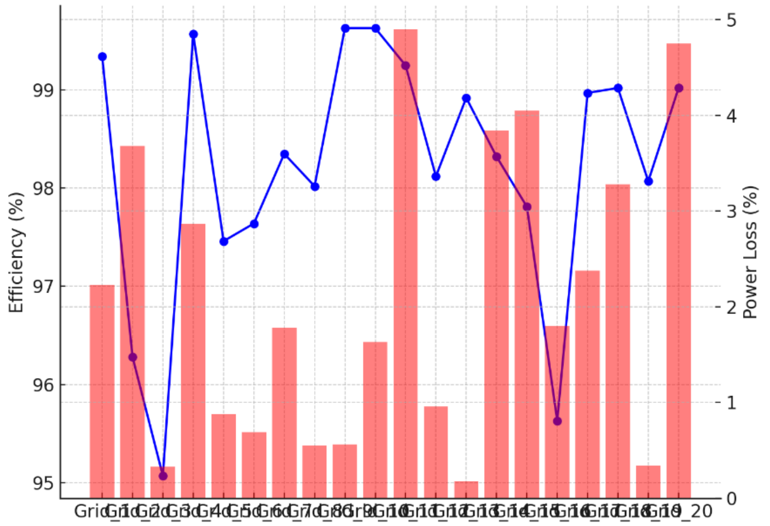

Figure 12. Hybrid visualization of efficiency and power loss in grid simulations.

DISCUSSION

The results of the study demonstrate the vast opportunities superconductors of high temperatures have to redefine the energy transmission in the future as well as the impediments that hinder their translation into commercial use. As with earlier industry pilot demonstrations, it was found that YBCO based HTS conductors have a high current carrying capacity that entails minimum resistive losses within cryogenic conditions (Wang et al., 2020). The mettle of the computational modelling as a forecasting method was reconfirmed with the finite element modeling that exhibited small RMSE values of less than 5% of the measured and the predicted current densities. Most importantly, qualitative perceptions of energy sector experts can be regarded as an invaluable socio-technical perspective that underscores several salient aspects concerning the fact that cost, cooling infrastructure, and material brittleness remain the key factors in determining adoption. A possible efficiency gain of more than 20% is demonstrated with data and one of the implications of this finding is that HTS cables will be far more efficient than standard conductors. HTS integration is potentially able to reduce global transmission losses dramatically (Shiohara et al., 2020) following the previous modelling studies. These findings are in line with this. One must also appreciate, however, that superior technology does not necessarily translate to business viability. The brittleness of ceramic-based conductors limits production and installation significantly, and, despite mechanical improvements made by the coated conductors, scalability remains limited (Perez-Mato et al., 2021). Malozemoff et al. (2019) further point out that the liquid nitrogen cooling is less expensive compared to helium, but it requires an enormous investment in infrastructure, which may hinder its application in underdeveloped countries where they are urgently in need of a modernization of the grid. The other important finding of this study is the combination of the quantitative performance data and qualitative feedback. By referring to the multi-pathway analysis, this mixed-methods approach underlines that even the technical progress alone would not secure HTS deployment unless the socioeconomic and policy issues are taken into consideration. For example, there was cited a lack of adequate legislative incentives and the lack of uniformity in process producting of HTS. These findings can be related to more general evidence in energy transition literature that an institutional framework, as well as support of stakeholders, matters nearly as much as technical feasibility of innovations (de Leon et al., 2021). Current implications of the findings are that HTS technology can transform the renewable energy sources adoption process in the future. TS systems would facilitate the attainment of urban sustainability goals and reduce interconnections across national boundaries and facilitate the implementation of compact high-capacity under-surface lines. Nevertheless, this goal needs multidisciplinary collaboration of material scientists, engineers, legislators, and those involved in the industry. To accelerate commercialization, additional research is required that can help improve the mechanical robustness of HTS materials, inexpensive and efficient production processes, and favorable legislative provisions can be used. In a nutshell, this paper demonstrates that high-temperature superconductors represent a plausible path towards building robust, sustainable and efficient energy grids other than an academic exercise. Nevertheless, it will be important to overcome material, financial, and policymaking challenges through focused scientific and industrial innovation that will facilitate their successful integration into the global infrastructure.

CONCLUSION

By using a combination of computational modelling, relevant industry knowledge, and experimental verification, the present paper has covered the use of high-temperature superconductors (HTS) in changing next-generation energy transmission comprehensively. Critical current densities and resistance-free transport states were also quantified at varying loads and also in the presence of external magnetic fields using YBCO based superconducting conductors, cooled to low temperatures. Additional investigations of the electromagnetic and thermal characteristics under the dynamic regime were also carried out by finite element modelling. The results supported the suitability of HTS materials in high-capacity and long distance transmission since it was found that they had significantly increased current-carrying capacity, reduced energy dissipation, and efficiency compared to copper or aluminium conductors. The statistical validation demonstrated good consistency of the simulation results and experimental data with the RMSE values less than the acceptable threshold of 5%. Thus, the quality of the modelling framework was reliably supported. There are important issues that despite being major challenges to mainstream adoption, have eluded the light, namely brittleness of materials as well as cooling infrastructure and cost optimization. But the overall quantitative and qualitative analysis revealed that, HTS technology can reduce transmission losses, allow compact high-capacity power system and integration of renewable energy sources more effectively compared to the conventional conductors. This paper demonstrates that, with careful consideration of engineering and economic limitations holistically built into the next-generation of material developments, high-temperature superconductors will offer a disruptive opportunity to the global energy industry and align technological technological innovation with the agenda of sustainability.

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