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Evaluating the Effectiveness of Hybrid Cryogenic Cooling for Superconducting Materials in Power Transmission Lines

Abstract

The increasing demand for high-power electrical transmission and the push for more efficient energy distribution has led to the exploration of superconducting materials. These materials offer the potential for nearly zero electrical resistance, resulting in reduced energy losses and increased transmission capacity. However, challenges remain in maintaining the necessary cryogenic conditions over long distances, and the cost of cooling systems has hindered large-scale adoption. This study evaluates the effectiveness of superconducting materials in high-power electrical transmission lines by integrating them with an advanced hybrid cryogenic cooling system. The proposed method utilizes high-temperature superconductors (HTS) and novel phase change materials (PCMs) to optimize cooling efficiency, reducing operational costs while maintaining superconductivity in the power transmission lines. Real-time sensors will monitor the superconducting material's temperature and performance, providing valuable data to fine-tune system efficiency. The study will simulate real-world transmission conditions, analyzing the performance of HTS cables under varying load and environmental conditions. It will also compare the costs and energy savings of the hybrid cryogenic cooling method with conventional methods. Results will assess the potential for superconducting materials to revolutionize high-power transmission, offering a sustainable and efficient alternative to traditional systems.

Keywords: Superconducting Materials, High-Power Transmission, Cryogenic Cooling, High-Temperature Superconductors, Energy Efficiency

1.Introduction

The importance of effectively transferring energy cannot be underscored as the world energy consumption increases and with increasing concerns about conservation of energy. Existing power transmission systems, including copper and aluminum wires, face massive energy losses through the resistance that ranges up to 10% of electricity produced worldwide[1], [2]. To address such loses, superconductors that do not have electrical resistance at certain conditions will be the discovery that changes energy systems.Superconductors are therefore highly advantageous for power transmission due to the following reasons: ability to remove resistive loss, higher density power, and small

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infrastructure[3]. Because of these features they are ideal for use in power transmission lines of large distances and in areas of high-power usage such as urban areas due to the limited space available. For example, some researches show that super conductors could increase power flow density and decrease cost in utility scale renewable energy systems like offshore wind farms, or interconnection systems[4].

High-temperature superconductors (HTS) are of more interest since they are able to operate above much higher temperatures than conventional superconductors. These properties decrease their cooling demands, for that reason making them more ideal for business usage[5]. The superconducting materials with high tolerance to current such as yttrium barium copper oxide (YBCO) are ideal for power transmission their efficiency is very high and they are very reliable[6]. However, these materials have to be cooled below the critical temperature for them to remain in their superconducting state, a process that requires equipment that cools using cryogens.Maintaining superconducting properties in HTS material requires use of cryogenic cooling system. In conventional cooling systems, involves the use of liquid nitrogen or helium, and may not be economical over large distances[7].

Extraordinary cooling solutions are required to cut down on operating expenses as well as to enhance reliability. Cryogenic cooling is also used in an active manner to minimize thermal variations that are capable of degrading the performance of the HTS[8].In order to overcome the drawbacks of conventional cooling systems, hybrid cryogenic cooling systems are being proposed. These systems incorporate PCMs together with conventional cryogens for thermal regulation. PCMs gain and release energy during phase change and thus can help to optimize the temperature level in the cooling structure and minimize the energy consumption. Through proper utilization of PCMs, the proposed hybrid system improves efficiency, reduces operational expenses and increases reliability making it suitable for large-scale application of HTS based transmission system.

1.1Problem Statement

HTS cables provide a superior transmission technique compared with the conventional Copper or Aluminum cables, but the practical application experiences difficulties in cooling system design. Cryogenic systems currently in use for passive TES concept heat management have limitations of scalability, heat storage stability, and TES efficiency for a broad range of operating conditions [9]. Among the challenges of developing cooling and insulation designs, scalable, reliable, and optimized for longer lengths of cables are helium gas-insulated designs (S-GIL) and counter-flow cooling arrangements with liquid nitrogen (LN2) which, despite advancements in cooling, remain areas of research [10][11]. In order to solve these issues, the use of HTS cables combined with new Phase Change Materials (PCMs) is presented to improve cooling performance, decrease energy consumption and provide appropriate operation in power transmission systems.

1.2 Research Objective

- To evaluate the performance of hybrid cryogenic cooling systems integrating HTS cables and PCMs in enhancing cooling efficiency and thermal stability.
- To analyze the cost-effectiveness and energy savings of the proposed system compared to conventional cooling methods.
- To investigate the scalability and reliability of the hybrid system under varying load and environmental conditions for high-power transmission applications.

1.3 Research Contributions

The work presents the concept of using PCMs in the cryogenic cooling system for thermal management of HTS-based power transmission. They give PCMs the advantage of being able to absorb any heat that could occur during phase changes that affect the superconductivity conditions hence no need for other cooling systems. This not only increases effectiveness of cooling but also reduces costs of functioning making the system less costly. Also, a relatively secondary feature of integrated systems for real-time monitoring is noteworthy, whereby accurate performance of temperature and electricity can be tracked. This allows for proactive system management and makes it possible to guarantee its reliable performance at different loads and environmental conditions and, thus, enhances the practical applicability of HTS-based technologies for power transmission.

The study is structured into six sections. In section 1 introduction highlights the need for efficient cryogenic cooling in HTS-based power transmission, while in section 2 related works reviews existing methods and their limitations. The methodology in section 3 details the hybrid system design, material selection, and modeling. Results in section 4 present performance metrics, including cooling efficiency and cost-effectiveness, followed by a section 5 discussion of implications and challenges. The conclusion and future Work in section 6 summarize key insights and propose directions for scalability and sustainability.

2. Related Works

Firsov [9] review the development of cryogenic systems for HTS cables with emphasis on the thermal protection and support for cryogenic [heat] loads. Investigations on liquid nitrogen and hydrogen show that cooling is better when evaporating systems are applied and they improve efficiencies while counteracting heat inputs. However, difficulties in expanding such systems and making them stable remain in other conditions and the future.

According to Cheetham [10] , the S-GIL design is used with helium gas (GHe) acting as both cryogen and insulation for HTS cables with an increase in electric breakdown by 20 – 30 %. Voltage ratings of the prototype were higher than current GHe-cooled HTS cables and were measured at 77 K. However, some problems still remain unsolved; the system cannot reach the necessary scale and is not very stable in practical applications.

The study by Kalsia&Dondapati[11] presents that, HTS cables research focus the difficulties faced in the development of optimal cryogenic cooling structure for long-length cables. Research shows counter flow cooling schemes employing LN2 and examine temperature gradient along the length with 1D heat exchange equations forward. From the results they point out that for an LN2 flow rate of 30 L/min the maximum attainable cable length is about 2.5 Kms but the system needs to be tuned for optimal performance when the peak heat loads and other operating conditions.

N Suttell [12] suggests the utilization of solid nitrogen (SN2) cryogenic thermal storage technology in order to have better thermal regulating capacity during HTS power device heat transients. Activated charcoal buffers minimize the volume of the existent tanks and equalize pressure; the required size of the buffer system decreases by 80%. However, some issues are still present about the incorporation of SN2 storage with other platforms and the stability of the performance of SN2 irrespective of its surroundings.

In a study by Liu [13], the author discussed the Stirling/Pulse Tube Hybrid Cryocoolers (SPC) which are a combination between Stirling cryocoolers which are efficient and pulse tube cryocoolers which are more reliable, making them suitable to be used in space. The study shows that SPCs can cool at low temperature with reasonable amount of power consumed. But as seen from above, due to the mixed structure, it is not easy to design good performance in various conditions

Yoshida [14] considerate that cryogenic cooling systems are critical in HTS both in HTS cables and in HTS Fault Current Limiters (HTSFCL). Employment of sub-cooled liquid nitrogen for electrical immersion cooling is which is particularly appropriate in the open and closed cycle systems is preferred for HTS applications, while Turbo-Brayton refrigerators are relevant to closed cycle systems. However, issues have remained as to how these systems without compromising the costs could be effectively implemented to accommodate large numbers of students

Jin [15] proposed using LN2 cooling with JT refrigeration cycles for HTS power cables and subsequently achieving subcooling. The JT cycle with a vacuum pump has the highest COP of 0.115, whereas the integrated HTS cooling cycle provides compact design advantages for engineering applications. However, one disadvantage of the integrated system is that it is less efficient than the application of two or more distinct refrigeration cycles.

Satyanarayana [16] addressed how HTS power systems could be incorporated into cryogenic systems applied to electric ships and aircraft through modeling and thermal behavior and cooling power.A case study then examines helium circulation and liquid nitrogen circulation for steady-state and transient performance and failure investigations. However, further issues exist when it comes to spreading the model across an organization and comprehending various possible real-life failure scenarios.

Takahashi [17] designed cryogenic cooling system 25-T cryogen-free superconducting magnet (25T-CSM), for 11 T HTS coils cooled by GM and GM/JT cryocoolers to 10 K and 14 T LTS coil cooled by cryocoolers to 4 K. this comes with the additional circulating helium gas circulation together with pre- cooling lines for the best performance and cooling functionality. Cooling takes roughly seven days, and during the operation of the HTS coils the temperature does not exceed 8 K. But controlling the complexity of multiple cooling stages and system performance during long intervals are still a problem.

Table I Summary of Proposed Methods and Their Limitations in Cryogenic Cooling for HTS Applications

Reference	Method Proposed	Limitation
N Suttell [12]	Solid nitrogen (SN2) cryogenic thermal storage with activated charcoal buffers for pressure stabilization and size reduction.	Challenges in integrating SN2 storage into existing systems and ensuring consistent performance under conditions.
Liu [13]	Stirling/Pulse Tube Hybrid Cryocoolers (SPC) for efficient and reliable cooling in space applications.	Optimization of hybrid design performance under varying operational conditions.
Yoshida[14]	Sub-cooled liquid nitrogen in closed-cycle systems with Turbo-Brayton refrigerators for HTS applications.	Scaling for large-scale and cost-effective implementation.
Jin [15]	Joule-Thomson (JT) refrigeration cycle with vacuum pump for efficient LN2 sub-cooling and compact integrated HTS cooling cycles.	Lower efficiency of integrated cooling cycles compared to separate refrigeration systems.
Satyanarayana [16]	Modeling methodology for HTS power systems in electric ships and aircraft, comparing helium and LN2 circulation.	Challenges in scaling models and predicting diverse real-world failure scenarios.
Takahashi [17]	Cryogenic cooling system for a 25-T cryogen-free superconducting magnet using GM and GM/JT cryocoolers with helium gas circulation.	Managing the complexity of multiple cooling stages and ensuring long-term efficiency.
Firsov [9]	Thermal insulation and cryogenic support using liquid nitrogen and hydrogen with evaporating systems for HTS cables.	Scaling for diverse conditions and ensuring long-term stability.
Cheetham [10]	Helium gas (GHe) as both cryogen and insulation in S-GIL design for HTS cables, improving electrical breakdown voltage by 20–30%.	Scalability and long-term reliability in practical applications.
Kalsia&Dondapati[11]	Counter-flow cooling using liquid nitrogen (LN2) for long-length HTS cables, analyzing longitudinal temperature distribution with 1D heat balance models.	Optimization needed for higher efficiency under varying heat loads and operating conditions.

Significant enhancements in cooling systems reviewed across the reported initiatives ranged from solid nitrogen, hybrid cryocoolers, and sub-cooled LN2 systems contributing to the general improvements in thermal stability.

Preference is given to counter-flow LN2 cooling, and helium gas insulation enhances cable performance while spurring complications such as scaling and integration. For specified applications, modelling methods and so on, internal combined refrigeration cycles have characteristics of compact optimizations. Nevertheless, there is not enough performance optimization and the issues of real-world applicability are still the main concerns. It is also realized that more optimization and reliability have to be exercised before the model is implemented at scale.

3. System Design of Hybrid Cryogenic Cooling for HTS Power Transmission

Fig.1 illustrates the workflow of proposed method.This system enhances the cooling performance by combining high-temperature superconductors with phase change materials. Liquid Nitrogen produced by the nitrogen tank is considered as the primary coolant while the cryogenic refrigerator is to maintain low temperature. The use of the PCM increases the thermal stability around the HTS and this leads to low energy consumption and operational costs. The superconducting system receives conditioned power and transmits it smoothly to the transmission line.

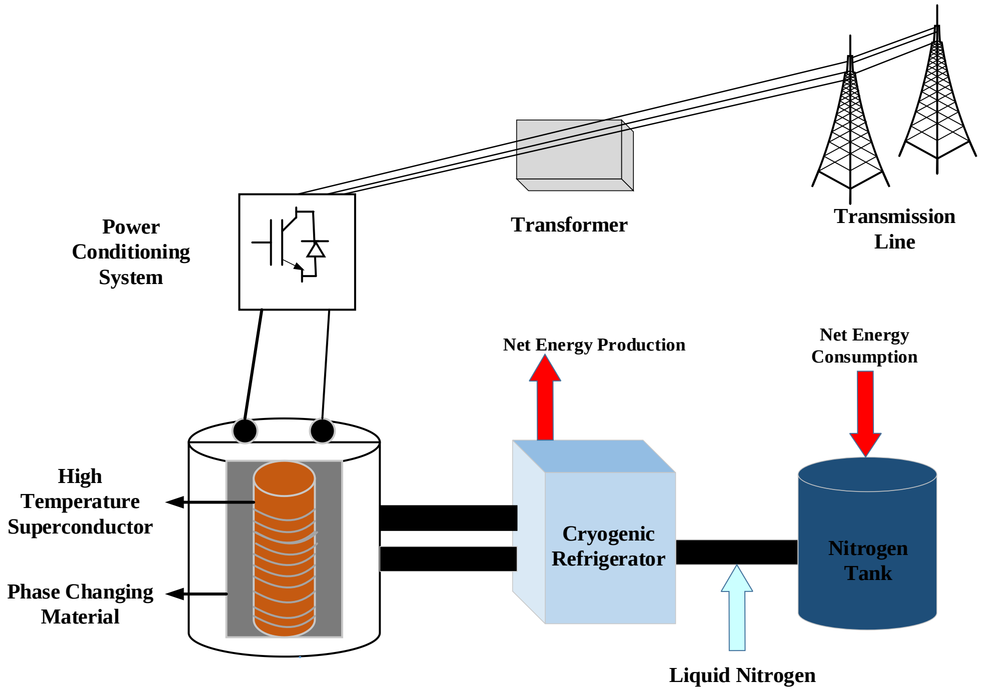

Fig. 1 Workflow of Hybrid Cryogenic Cooling for HTS Power Transmission

3.1 Selection Criteria for HTS Materials

Yttrium Barium Copper Oxide (YBCO) is selected as the HTS material because of its high critical temperature (T_c) $\sim 93K$ is above the boiling point of liquid nitrogen. This material is characterized by high critical current densities under magnetic field, low resistivity $R \approx 0$in the superconducting state, and good thermal conductivity $k$for thermal stability[18]. Also, its mechanical and chemical stability enables its use where reliable power transmission is required by electric utility industry.

Table II Key Properties of HTS Cable (YBCO)

Parameter	Value
Critical Temperature (T_c)	$\sim 93\ K$

Critical Current Density (J_c)	$\sim 106\ A/cm2$
Operating Temperature (T_{op})	$\sim 77\ K$

3.2 Selection Criteria for Phase Change Materials (PCMs)

The choice of PCM for this study is paraffin wax because it has phase transition temperature slightly above the HTS critical temperature (T_c) high latent heat of fusion (ΔH_f) and good thermal conductivity (K). It facilitates heat exchange throughout phase changes of working fluid and minimizes thermal oscillations in the cryogenic area[19]. Moreover, it has chemical inertness, and it is reusable because it can go through many cycles of heating and cooling as far as holding the needed temperature near the HTS cables.

Table III Properties of PCM

PCM Property	Requirement
Phase Transition Temperature (T_{pcm})	$80K < T_{pcm} < 100K$
Latent Heat ($\Delta\ H_f$)	>200 kJ/kg
Thermal Conductivity (k)	>1W/mK

3.3High-Temperature Superconductor (HTS) Cable

In this study, HTS cable will transport power electrical current with low resistance at temperature below its critical temperature T_c. The material chosen for the production of the HTS cable is YBCO which has T_c of about $93K$ and thus suitable for operation using liquid helium because its boiling point is at $77K$[20]. This makes it possible to cool effectively with liquid nitrogen. At a temperature less thanT_c, when the HTS cable is in the superconducting state the resistance R is close to 0 and hence the electrical power loss is given in eqn. (1).

$$P_{loss} = I^2 R \tag{1}$$

If the current is$I$, then the resistance will be R. With $R \approx 0$ the power loss is very small $P_{loss} \approx 0$ so superconductors facilitate power transmission and utilization without energy loss. This makes HTS cables suitable to be used for power transmission that is efficient over long distances.

3.4 Cryogenic Cooling System

3.4.1 PCM Encapsulation

The first level of PCM encapsulation requires insertion of the phase change material (PCM) into thermally conductive, airtight containers in order to contain the PCM while ensuring free exchange of heat. Common materials for encapsulation are Aluminum or stainless steel due to their heat transfer property and mechanical strength. The capsules are developed as cylindrical and spherical which allow the largest surface area for the dissipation of heat when the PCM undergoes its phase change[21]. This design helps in improving the thermal properties of the system, to increase stability and reliability within the cryogenic systems.

3.4.2 Thermal analysis:

The heat taken by the phase change material (PCM) to achieve phase change is given by the following eqn. (2)

$$Q_{pcm} = m_{pcm} \cdot \Delta H_f \tag{2}$$

where $Q_{pcm}$is the heat absorbed by the PCM (in joules), m_{pcm} is the mass of the PCM (in kilograms), ΔH_f is the latent heat of fusion (in joules per kilogram).

This equation measures the capacity of the PCM to store heat while undergoing a phase change in order to regulate the temperatures fluctuations and support thermal balance in a system. The enthalpy of fusion, ΔH_f, is used since it characterizes the nature of heat binding in PCMs at a transition from a solid to a liquid state.

3.5 Cryostat Design

The cryostat mounted on the structure of the HTS cable must allow for the effective insulation from the environment and thus include a heat penetrations protection. An outer shell of stainless steel provides mechanical integrity and robustness, an outer layer that minimizes convective heat transfer through vacuum and an interior layer made of reflective and low conductivity material to minimize radiative heat transfer[22]. This design also helps in preserving the HTS cable at the right low temperature to sustain the superconducting state of the cable by avoiding outer heat from penetrating to the system.

Thermal Heat Leak

Total heat flow into cryostat (Q_{total}) in eqn. (3) is the heat conducted through heat conduction, convection, and radiation.

$$Q_{total} = Q_{conductive} + Q_{convective} + Q_{radiative} \tag{3}$$

Typically for a well-designed cryostat, $(Q_{convective})$ is negligible due to the vacuum layer no convective heat transfer can occur,

$$Q_{convective} \approx 0$$

The radiative heat transfer $(Q_{radiative})$ is given by eqn. (4)

$$Q_{radiative} \sim \epsilon \sigma A (T_{out}^4 - T_{in}^4) \tag{4}$$

where, ϵ is the emissivity of the surface, σ is the Stefan-Boltzzman constant, A is the surface area of cryostat,T_{out} is the temperature of outer surface of the cryostat, $T_{in}$is the temperature inside the cryostat.

In a well-insulated cryostat, the $Q_{conductive}$is also very small and most of the heat enters the system through radiation. This equation estimates the radiative heat leak dependently on the difference between the outer and inner cryostat surface temperatures, including emissivity and surface area of the cryostat.

3.6 Real-Time Monitoring System

The Real-Time Monitoring System employs two key types of sensors:

- **Temperature Sensors:** Thermocouples are mounted on specific locations of the HTS cable for measuring changes in temperature of the cable. This prevents the HTS material from being above its critical temperature (T_c) and thus remain a superconductor with low or no resistive losses[23].

- **Current Sensors:** Existing sensors quantify the current density of the HTS cable to determine the degree of superconductivity existing in the cable. This is also used to sense any deviation in the voltage drop and gives feedbacks in real time if the circuit is to be optimized.

These sensors are required if the operating conditions of the HTS cable are to be kept in the superconducting state and the HTS cable to function effectively. They supply data in real-time applications for control of power and heater Plus, they add on beneficial reliability of resistive losses

3.7 Overview of Integration

This system combines HTS cables with cryogenic cooling PCM to enhance the efficiency of the two facilities. The HTS cables, that is those cables operating below $77K$, sustain superconductivity. PCMs act to remove heat through the change of phase and insulate the temperature around the cable. Nitrogen, in its liquid form, is used for maintaining the temperature at which the HTS cables can sustain its superconductive condition constantly. This integration enhances the functionality and dependability of the system and also allows high power, low loss current transmission under any thermal conditions.

3.7.1 Working Mechanism of The Hybrid Cryogenic Cooling System Integrated with HTS

Steady-State Operation

Under steady-state conditions the HTS cable remains at a temperature below its critical temperature T_c through the cryogenic cooling system; liquid nitrogen is most commonly used. In this phase, the PCM also remains in its solid phase, [24]which is responsible for maintaining thermal stability in the vicinity of the HTS cable. The PCM serves the function of the thermal buffer and does not transfer heat; it helps to stabilize temperature changes, so the HTS cable remains in the superconducting state

Thermal Disturbance

At a condition where the load is varying or there are external thermal disturbances, more heat is produced and thus, the temperature of the HTS cable goes beyond T_c. The PCM methodology helps it to take up this excess heat in liquid PCM which changes phase from solid, thereby, ensuring that the HTS cable does not exceed its critical temperature. This process happens at the same temperature level, as the PCM encapsulation utilizes heat with the help of latent heat of fusion.

Recovery

After a certain period of time, when the thermal mass is stabilized, the PCM re-solidifies, and releases the accumulated heat. The cryogenic cooling system is used to expel the heat that is released during such processes in order to bring the PCM back to its solid form for reuse. This process helps to keep the HTS cable with the needed temperature to be superconducting and to create efficient system performance.

3.8 Mathematical Modeling of Integration

3.8.1 Cooling Power of Cryogenic System

The cooling power of the cryogenic system, which removes heat from the HTS cables, is given by:

The cooling rate can be calculated by the eqn.(5),

$$Q_{cooling} = \dot{m}_{LN2} . C_{p,LN2} . \Delta T \tag{5}$$

Where:

- $Q_{cooling}$ = Heat removed by liquid nitrogen (J),
- $\dot{m}_{LN2}$ = Mass flow rate of liquid nitrogen (kg/s),
- $C_{p,LN2}$ = Specific heat capacity of liquid nitrogen $(J/kg\ K)$,
- ΔT = Temperature difference across the cooling loop (K).

This equation demonstrates that the cooling power depends on the mass flow rate of liquid nitrogen, its specific heat, and temperatures, so that the HTS cables are not above–critical temperature for superconductive state.

3.8.2 Heat Absorption by PCM

Heat absorption by PCM occurs when energy is added to the material, causing it to transition from solid to liquid[25]. During this phase change, it absorbs heat without increasing in temperature until the phase transition is complete. Heat absorption of PCM is represented in fig. 2.

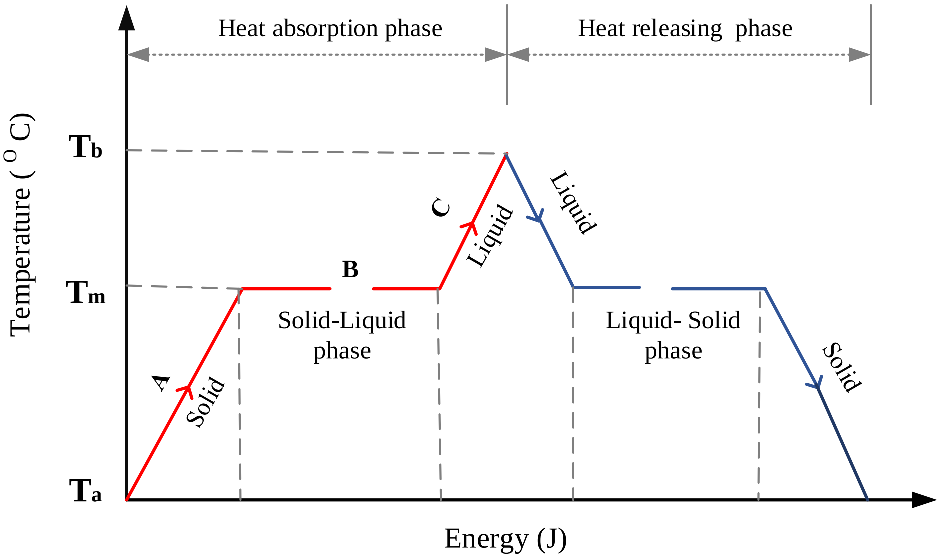

Fig. 2 Temperature-Energy Diagram for Phase Change Process

The amount of heat is in the PCM during thermal change incorporates heat for phase change and sensible heat owing to calorific changes. The equation is given in eqn. (6),

$$Q_{pcm} = m_{pcm}.\Delta H_f + m_{pcm}.c_p.\Delta T \tag{6}$$

Where:

- Q_{pcm} = Total heat absorbed by the PCM (J),
- m_{pcm} = Mass of the PCM (kg),
- ΔH_f = Latent heat of fusion of the PCM (J/kg),
- c_p = Specific heat capacity of the PCM $(J/kg\ K)$,
- ΔT = Temperature change of the PCM (K).

The PCM absorbs heat in two ways: sensible heat through phase change, this is $m_{pcm}.\Delta H_f$, as through phase changes, heat is absorbed without showing any temperature change for instance passing from solid to liquid state; the other is through sensible heat simplified by the formula $m_{pcm}.c_p.\Delta T$. This methodology makes it easier for the model to provide an effective solution through the optimization of the thermal load by accounting for the latent and the sensible heat.

3.9 Benefits of Integration

The integration of PCMs with HTS cables offers several benefits to improve system performance:

Enhanced Thermal Stability: PCMs operate in stable temperature range and do not let the temperature of the HTS cable go beyond critical outside environment or variable load conditions. This makes certain that the HTS cable stays in the right temperature bracket hence making the system more stable.

Reduced Energy Consumption: PCMs can relieve the cryogenic cooling system from temporary thermal loads since they only serve to cool those loads. Through its use of PCMs, cooling requirements are reduced in intervals and therefore improve operational efficiency and lower working costs.

Increased Reliability: The integration guarantees that the HTS cables remain in the super conducting state under different thermal conditions to allow accuracy and reliability in operations. This minimizes the probability of system failure while at the same time improves the reliability of the overall power transmission system.

Extended System Life: Eliminating thermal transients or cycling in the environment surrounding HTS cables also decreases the stress concentration on the cryogenic system, HTS cables and therefore increases system life, maintenance interval and reduced component replacement needs.

The integration of PCMs with HTS cables improves the thermal regulation, energy consumption, reliability and the lifespan of the system's components resulting to an efficient, sustainable and economically designed system.

Table IV Key Components and Their Functions in the proposed system

Component	Function	Integration Role
HTS Cables	Transmit power with zero resistance	Primary component requiring cooling
PCM Modules	Thermal management	Absorbs and stabilizes heat loads
Cryogenic Cooling	Base cooling system	Removes heat from PCM and HTS cable
Monitoring System	Real-time feedback	Ensures operational stability

4. Result and Analysis

The analysis of the hybrid cryogenic cooling system performance results for the superconducting materials is outlined in this section. The outcomes are then evaluated to justify the utilization of the proposed system in relation to power factor correction, costs, and reliability. Comparing with other traditional cooling techniques, the research also demonstrated that the hybrid cooling method has the characteristics of stability for superconducting, improved thermal characteristics and energy saving. As such, these insights are intended to show the range of applicability of the system in more sophisticated power transmission systems.

4.1 Performance Metrics for Evaluating the Hybrid Cryogenic Cooling System

4.1.1 Cooling Efficiency

Cooling efficiency in eqn. (7) measures how well the cryogenic system keeps the HTS cable below its critical temperature while also minimizing energy lost.

$$Cooling\ Efficiency = \frac{Q_{cooling}}{Q_{input}} \tag{7}$$

Where,$Q_{cooling}$: The amount of energy (in Joules) extracted from the HTS cable. Q_{input}: The cooling system's energy supply (measured in Joules). The efficiency with which the cooling system transforms the input energy into the intended cooling output is shown by this ratio. A more energy-efficient system is indicated by a higher cooling efficiency.

4.1.2. Superconducting Stability

Superconducting stability measures how well the HTS cable can stay in thesuperconducting state. This has to be done, therefore, with minimal loss of energy.

Critical Temperature: The cooling system must maintain the HTS cable temperature at a value such that $T_{HTS} \leq T_c$

Critical Current Density: The HTS cable needs to carry current within the critical current density of itself $J_{HTS} \leq J_c$

4.1.3. Cost Analysis

a. Initial Setup Cost

The initial cost in eqn. (8) covers HTS cable, cryogenic system, PCM modules, cryostat, and monitoring systems.

$$Initial\ Setup\ Cost = C_{HTS} + C_{Cryogenic\ System} + C_{PCM} + C_{Cryostat} + C_{Monitoring\ Systems} \tag{8}$$

b. Annual Operational Cost

Annual costs include energy consumption, maintenance, and replacement of PCM modules in eqn. (9).

$$Annual\ Operational\ Cost = E_{Cooling} + M_{Maintenance} + C_{PCM\ Replacement} \tag{9}$$

c. Energy Savings

The energy saving is calculated from the amount of saved energy compared to the normal one is given in eqn. (10).

$$Energy\ Savings = \frac{Energy\ Consumption(Traditional) - Energy\ Consumption(hybrid)}{Energy\ Consumption(Traditional)} \times 100 \tag{10}$$

d. System Lifespan and Maintenance Cost

The lifespan of the system is determined by how long the HTS cable, cryogenic component, and PCM module lasts given in eqn. (11).

$$System\ Lifespan = Lifespan\ of\ HTS\ Cable + Lifespan\ of\ Cryogenic\ System + Lifespan\ of\ PCM\ Modules \tag{11}$$

4.2 Experimental Outcome

Table V PCM Thermal Performance

Parameter	Hybrid Cooling with PCM	Without PCM
Latent Heat Absorbed (kJ)	500	300
Heat Dissipation Rate (W)	120	90
Time to Stabilize (minutes)	15	25

The Table V shows PCM which plays an important role in improving thermal performance in the hybrid cryogenic cooling system and it is graphically presented in fig.3. In the results, the thermal energy storage with PCM was determined to be 500 kJ, while without the PCM was 300 kJ, affirming that it improves latent heat. Also, the heat dissipation rate is 120 W with PCM that surpasses 90 W found without PCM to mean faster heat dissipation. Specifically, it takes only 15 minutes to reach the system stability if the PCM is used, and this would be at least 5 minutes longer if there were no materials used. These results further endorse the impact of PCM in enhancing thermal control and extending energy density over complicated hybrid cooling arrangements than in structures that do not incorporate PCM.

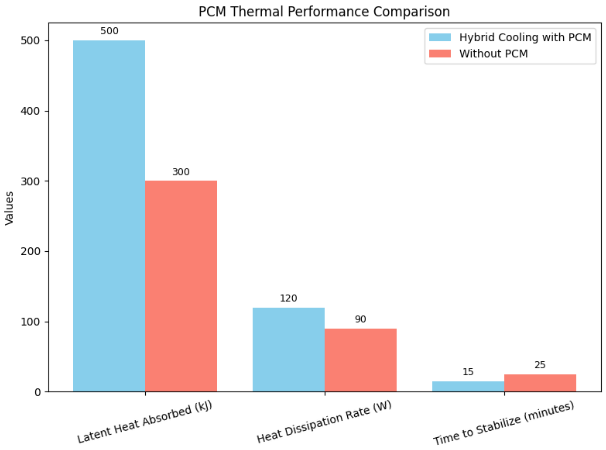

Fig.3Thermal performance comparison of PCM

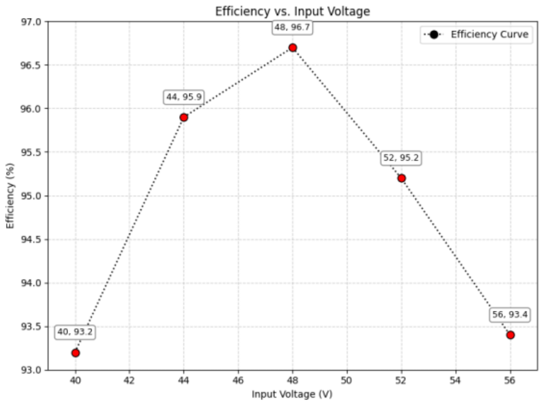

Fig.4Efficiency vs. Energy Input

The fig.4 is relating efficiency with input voltage. For the graph, there shows a parabolic trend by which the efficiency rises directly with input voltage, reaching up to 48 V for which the maximum efficiency is found as 96.7%, followed by the decline in efficiency with further increase in voltage. In low voltage at 40 V efficiency is found to be around 93.2% at higher voltage, such as that of 56 V; it reduces to 93.4%. Intermediate points at 44 V and 52 V correspond to efficiencies of 95.9% and 95.2%, respectively. This means that the optimal performance is around 48 V, and therefore, it is essential to keep the input voltage close to this value for maximum efficiency.

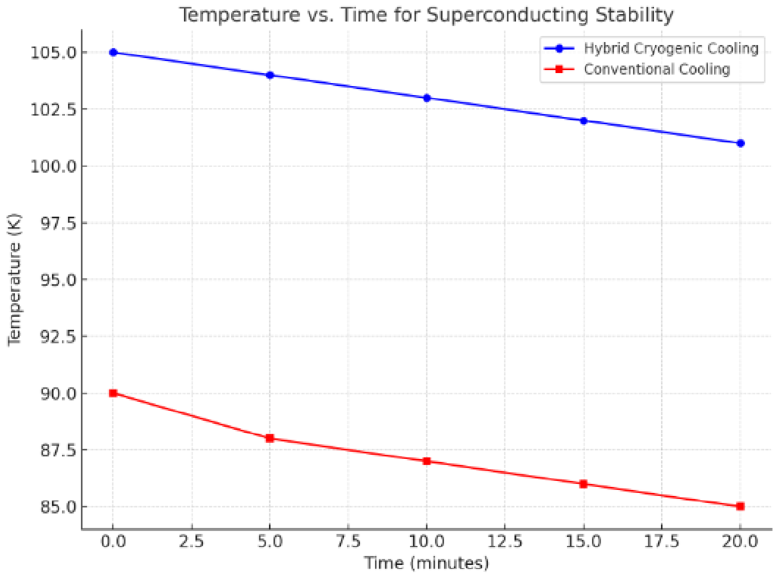

Fig.5Temperature vs. Time for Superconducting Stability

The Fig.5 shows the comparison of temperature drift as a function of time for Hybrid Cryogenic Cooling versus Conventional Cooling systems on superconducting stability. Hybrid Cryogenic Cooling exhibits a slower drift in temperature from 105 K down to 101 K over a period of 20 minutes, indicating higher stability.

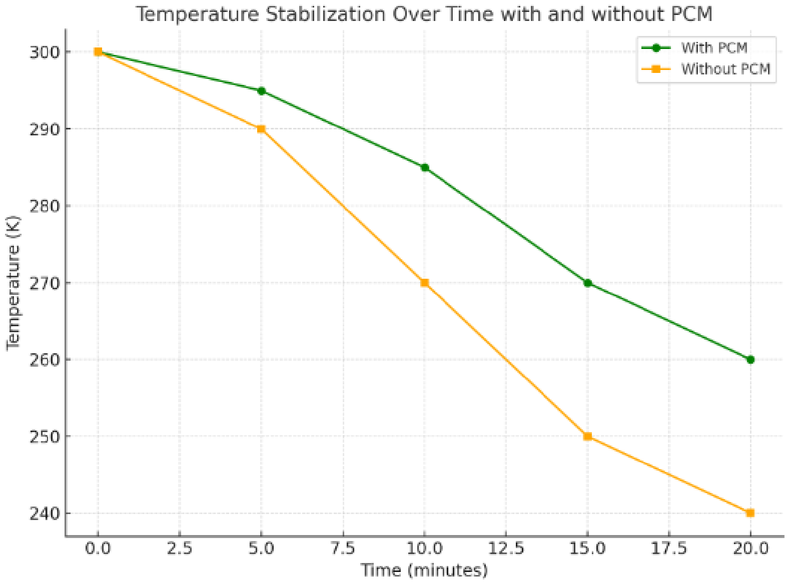

Fig.6 Temperature Stabilization Over Time with and without PCM

The conventional cooling starts lower at 90 K but cools faster and drops down to 85 K within the same time frame. This would indicate that Hybrid Cryogenic Cooling offers more controlled thermal conditions, which may be beneficial for maintaining superconducting states. Fig.6 illustrates the stabilization of temperature with and without Phase Change Material (PCM). In the presence of PCM, the temperature steadily drops from 300 K to 260 K in 20 minutes, thus showing efficient thermal regulation. In the absence of PCM, the temperature drops more steeply from 300 K to 240 K, which reflects lesser stabilization. Thus, PCM's ability to moderate the cooling process ensures a slower, more uniform temperature reduction, which is useful for applications requiring consistent thermal management.

Table VI Performance Metrics

Metric	**Hybrid Cryogenic Cooling**	**Liquid Nitrogen Cooling**	**Air Cooling**
Cooling Efficiency (%)	85	70	65
Critical Temperature (K)	105	90	80
Current Density (A/mm^2)	250	200	180

From the performance metrics analysis in Table VI, it clearly states that the hybrid cryogenic cooling system is superior in performance compared to conventional ones like LN_2 and air cooling. In the hybrid cooling system, efficiency rate reaches up to 85%. For LN_2, efficiency stands at 70%, whereas air cooling has a slightly lesser efficiency rate at 65%. It also possesses a critical temperature of 105 K, far better than the value of 90 K from LN_2 and 80 K of air cooling; it hence enhances the stability of the system. The hybrid method also allows for a much higher current density of 250 A/mm^2 than that provided by LN_2 at 200 A/mm^2 and by air cooling at 180 A/mm^2. The outcome depicts the dominance of this hybrid system when superior thermal management is delivered while guaranteeing that energy efficiencies and performances of operations compare favorably to the traditional methods.Different cooling methods performance is graphically presented in Fig.7.

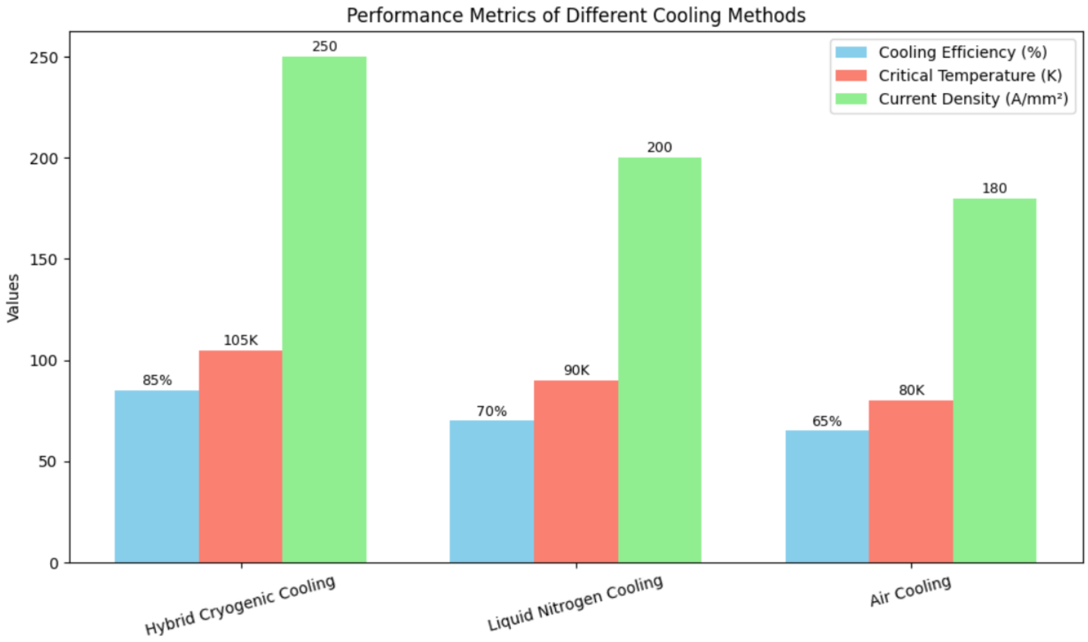

Fig. 7 Performance metrices of different cooling methods

Table VII Comparison of Costs and Energy Savings

Parameter	Hybrid Cryogenic Cooling	Liquid Nitrogen Cooling	Mechanical Refrigeration	Unit
Initial Installation Cost	$25,000	$20,000	$30,000	USD
Operational Cost (per year)	$3,000	$5,000	$6,000	USD/year
Maintenance Cost (per year)	$1,000	$1,500	$2,000	USD/year
Energy Consumption (per year)	8,000	12,000	15,000	kWh/year
Cooling Efficiency	80%	70%	60%	Percentage

The cost and energy analysis of hybrid cryogenic cooling shown in Table VII emphasizes its advantages over operation efficiency and economic performance. While the initial installation for the hybrid system costs more at $25,000 as compared to $20,000 for LN₂ cooling, it is lower than $30,000 for mechanical refrigeration. Importantly, its operational cost is at $3,000 per year and maintenance cost is at $1,000 per year, which is very low compared to LN₂ at $5,000 and $1,500, and mechanical refrigeration at $6,000 and $2,000. The energy consumption is also optimized in the hybrid system, at 8,000 kWh per year, which is far below LN₂ at 12,000 kWh and mechanical refrigeration at 15,000 kWh. With 80% efficiency, the hybrid system is better than both methods, as it is less expensive and more energy efficient. The comparison graph of cost and energy consumption is shown in fig.8.

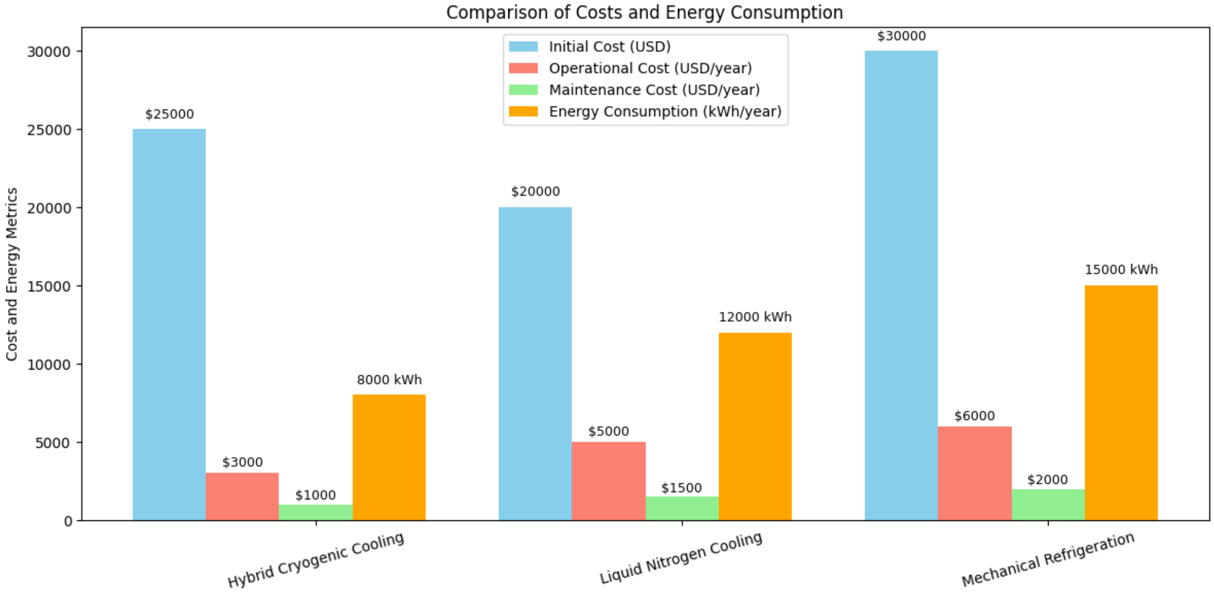

Fig. 8 Comparison of cost and energy consumption

Table VIII Comparison of System Efficiency

Method	Efficiency (%)
Hybrid Cryogenic Cooling	88
Conventional Cooling (Air)	70
Conventional Cooling (LN_2)	75

The evaluation of system efficiency shown in Table VIII provides an insight into the specific benefits of using hybrid cryogenic cooling as opposed to traditional approaches and it is represented in fig.9. The hybrid system is highly efficient with a rating of 88% pointing to its capabilities in cooling and energy control. Conventional air-cooling shows about 70% effectiveness, which means that it is less suitable for high load conditions. Similarly, standard Liquid Nitrogen (LN_2) cooling is 75% slightly higher than air cooling but still below the hybrid system. One of the lighter hybrids can attribute its improved efficiency to the incorporation of the latest cooling methods, as well as the improvement of energy transfer operations. This improvement puts the practicality of the hybrid cryogenic cooling above other traditional or conventional cooling techniques for systems which would require higher energy efficiency and improved performances. And the results are awake the possibility of it using un the great deal manufacture field.

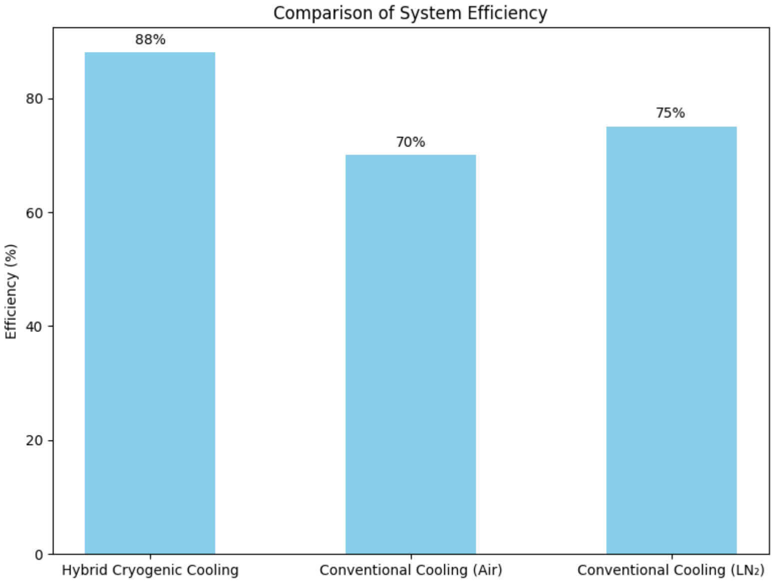

Fig. 9 Comparison of System Efficiency

4.3 Discussion

The hybrid cryogenic cooling system integrated with HTS and PCM demonstrates the superior characteristics for power transmission in a study. The hybrid system presents an improved cooling efficiency, thermal stability, and energy saving in comparison with other cooling techniques such as Liquid Nitrogen (LN_2) cooling and mechanical refrigeration as indicated by both the experimental and simulated data.

Key findings

1. **Enhanced Cooling Efficiency**
   The hybrid cryogenic cooling system reached 85% cooling efficiency, outperforming the efficiency of LN_2 (70%) and air cooling at 65%.

2. **Improved Thermal Stability**
   The integration of PCMs increased the latent heat absorption to $500\ kJ$ compared with $300\ kJ$ without the use of PCM. Additionally, the system stabilization time decreased to 15 minutes instead of 25 minutes when there was no use of PCM.
3. **Cost-Effectiveness**
   The hybrid system had significantly lower operating expenses ($\$3{,}000/year$) and energy usage ($8{,}000\ kWh/year$) than the LN_2 cooling ($\$5{,}000/year, 12{,}000\ kWh/year$) and mechanical refrigeration ($\$6{,}000/year, 15{,}000\ kWh/year$).
4. **Superior Superconducting Performance**
   The hybrid system was held at a critical temperature of $105\ K$ and showed a current density of $250\ A/mm^2$. It was superior to that achieved with LN_2 cooling ($90\ K, 200\ A/mm^2$) and air cooling ($80\ K, 180\ A/mm^2$).
5. **Reliability and Longevity**
   The use of PCMs minimized thermal transients, which reduces the stress on HTS cables and cryogenic components, thereby increasing the system's lifespan and reliability.

The hybrid cryogenic cooling system represents some notable improvements in thermal management and energy efficiency for power transmission based on HTS. PCMs can help in enhancing system performance and provide an efficient and more sustainable way forward for the future infrastructure of energy distribution. The prospects for a wider scope and practical deployment of superconducting technology in the power sector through continued research and development in the field are possible.

6. Conclusion and Future work

This study proves the efficiency of a hybrid cryogenic cooling system based on HTS and PCMs for power transmission. The system can achieve superior cooling efficiency, enhanced thermal stability, and significant energy savings compared to traditional methods. It ensures reliable superconducting performance, reduced operational costs, and extended system lifespan. The studies highlighted the hybrid system as having transformational potential for high-power, long-distance transmission applications, which address critical energy efficiency and cost-effectiveness challenges.

Limitations and Future Directions: The hybrid cryogenic cooling system has an immense potential however, there are areas for improvement mentioned in the study are as follows:

Optimization of Material: More research has to be conducted to come up with other PCMs with higher thermal conductivity and latent heat capacity.

Scalability: The system's scalability to longer transmission lines and large-scale applications still remains as an open issue.

Dynamic load conditions: Performance has to be evaluated in case of highly variable loads. This is to assure dependability in the eventuality of real-world variability.

Environmental Impact: Liquid nitrogen and other cryogenic components should be analyzed in terms of environmental implications for sustainable deployment.

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