Contactless power supplies for low-voltage superconducting magnets

HTS flux pumps (HTS-FPs) are compact and contactless power supply systems, able to induce current in superconducting magnets. A preliminary design of a HTS-FP for the toroidal field coils of the Divertor Tokamak Test (DTT) facility showed a significant potential reduction of both capital (Capex) and operating (Opex) costs. The HTS-FP principle and the developed design procedure could be adopted in many applications involving superconductivity, even outside fusion.

Description of the technology

HTS flux pumps (HTS-FPs) are contactless power supply (PS) systems able to induce high currents at low voltage in low-temperature (LTS) or high-temperature (HTS) superconductor coils.

HTS-FPs share the same constructive principles of conventional electrical machines and act as power converters with a DC voltage output. Because of their inherent contactless and superconducting nature, HTS-FPs allow to reach energization and persistent or quasi-persistent current mode of superconducting magnets without exhibiting any loss during such regime.

HTS-FPs employ a traveling magnetic field wave to induce, after internal rectification using one or more HTS tapes, a small DC voltage at the terminals of the supplied magnet. Although HTS-FPs can produce limited values of voltage, typically lower than 1 V, it has been demonstrated that their output currents can reach tens of kiloamperes. This low voltage can be sufficient (and maybe optimal) to supply magnets with DC or low-dynamics operations, as toroidal field (TF) coils in tokamaks or stellarator coils. The design of an HTS-FP includes the production of a magnetic traveling wave using two distinct sets of copper coils, which are enclosed inside a ferromagnetic structure, as illustrated in Fig. 1. A commercial three-phase inverter (rated for few kilowatts) can be adopted to supply both the AC coils and the DC coil.

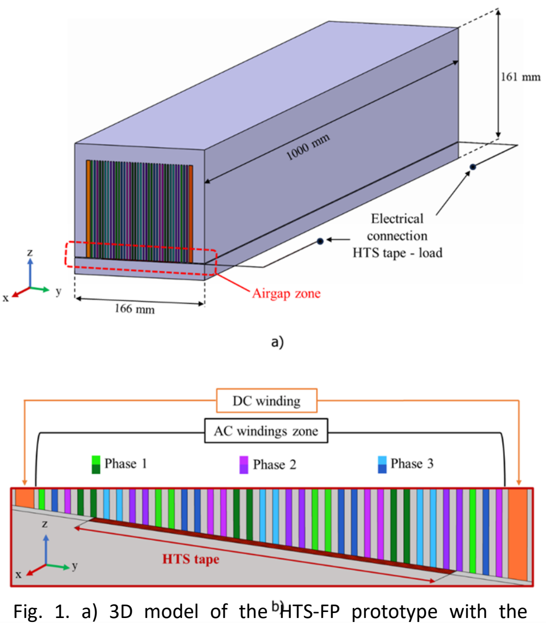

Fig. 1. a) 3D model of the HTS-FP prototype with the characteristic dimensions. b) Detailed view of the air gap area including the HTS tape and the phases of the exciter.

Characteristic	Designed HTSFP	Traditional DTT PS system
Output voltage	150 mV	≈100V
Efficiency	99.78% (1)	<5%
Ripple	<0.1%	>0.1%
Load coil charging (pre-magnetization) time	<15 minutes	20 minutes (2)
Power losses in on-state	2.5 kW	>10 kW
Energy losses during the entire ramp-up phase	540 Wh	>2 kWh (3)
Average power losses during the flat-top phase	5.8 W	>10 kW
Energy losses for a 30-year lifespan (4)	1.52 MWh	>1 GWh
Footprint	1×0.17×0.16 m	≈5×5×5 m

(1) Virtual average efficiency at flat-top.
(2) Even if shorter charges could be possible, a safe charge of the DTT TF coils are expected to take at least in 20 minutes.
(3) Dependent on ramp-up time.
(4) Estimated for a constant flat-top over the lifespan

Fig. 2. Summary of main charcteristics of the HTS-FP prototype, compared with those of the planned DTT power supply system.

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The scalability is one of the strengths of the HTS-FP device thanks to its very small size, weight, controlling simplicity and modularity. In fact, the basic developed design is rated for a current capability of 2 kA and can be conceived as one module that can be combined in a scalable manner with other identical modules in series/parallel, depending on the requirements of the superconducting magnet to be fed. Moreover, the HTS-FP design was implemented by exploiting the consolidated numerical modelling expertise of the team partners combined with machine learning optimization algorithms to address the specific needs of fusion magnets. The optimization control strategy of the HTS-FP was also investigated obtaining an and consisted of two states: on-state and off-state. When off, the copper coils are not supplied and the HTS-FP simply acts as a short circuit connection at the terminals of the magnet, whose current can flow without losses and without requiring any input power. In practice, the off-state realizes a quasi-persistent current mode with ideal efficiency. While on, the travelling magnetic wave is applied to the HTS tape inducing the output voltage. In this state, the efficiency can be calculated as the ratio between the HTS-FP output power to the magnet and the input power fed into the HTS-FP. During the current ramp up of a superconducting magnet, the HTS-FP needs to be in the on-state until its current reaches the rated value. Then, the HTS-FP can be switched to the off-state. Later, the on-state is periodically briefly re-activated only to compensate the slow decay of the current produced by the small resistance of the magnet due to joints. The overall efficiency of the HTS-FP results from the weighted average of efficiencies during on-state and the off-state (assuming 100% during off-state because of the absence of losses), where the weight is given by the durations of the two states (hence, by the control duty cycle). The results reported in Fig. 2 show that the average efficiency of the designed HTS-FP can exceed 99%, that is well above the traditional PS setups, resulting in a significant reduction of operating costs. At the same time, HTS-FPs can reduce system size and capital costs.

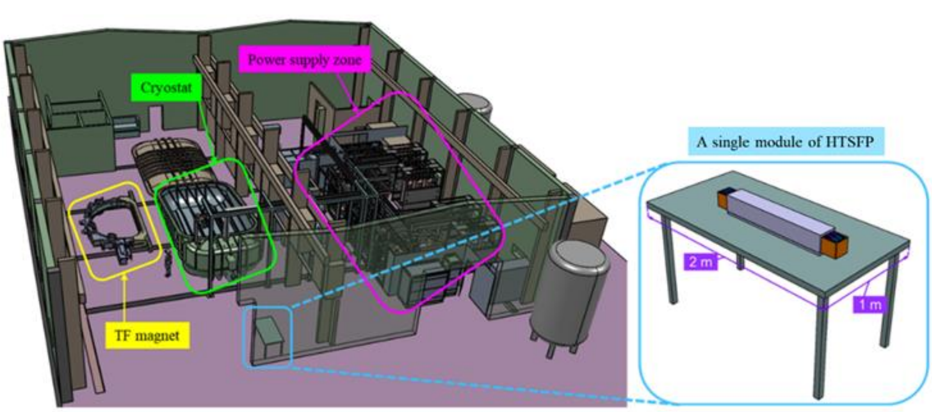

Fig. 3. Representation of a possible integration of the designed HTS-FP module (on table in blue box) within the DTT Cold Test Facility in comparison with the planned power supply system.

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Innovation and advantages of the offer

The traditional solutions used to supply superconducting magnets are affected by several drawbacks in terms of efficiency, footprint, and reliability. HTS-FPs can represent a very important step toward the practical exploitation of nuclear fusion as a viable and cost-effective energy source. Compared to traditional systems, which include bulky and expensive metal busbars supplied by inefficient grid-connected power converters, HTS-FPs drastically reduce both capital and operating costs.

By being contactless, HTS-FPs do not require high-current leads, which represent the major heat load inside the cryostat, and allow the operation of coils in persistent or quasi-persistent current mode without any dissipation. The proposed HTS-FP design was developed focusing on the DTT TF coils and the DTT Cold Test Facility.

Hence, the obtained characteristics and performances could be assessed by comparison with the power supply system of such facilities that are based on conventional technologies. It can be estimated that a system comprising 44 HTS-FP modules in parallel to meet the current requirement for the DTT TF coils would dissipate about 2.8 kW of electric power on average during current flat top, compared to about 300 kW for conventional systems, resulting in over 99% energy savings. This would significantly reduce the needs for water cooling and air conditioning and the heat buildup in confined spaces, improving the reliability of components. Footprint benefits are also strategic and are highlighted in Fig. 3: the designed HTS-FP module weights less than 250 kg and occupies only 0.03 m3. For reference, the solid-state power converters for the DTT TF coils have a footprint of almost 200 m2 while its busbars weight about 150 tons and occupy about 16.5 m3. In perspective, it would take 600 HTS-FP modules to match the weight of the copper busbars alone.

Additionally, HTS-FP systems reduce reactive power demand and harmonic disturbances, leading to further operational cost reductions. Finally, it is important to stress that the HTS-FP design procedure was based on flexibility and scalability to address different coil specifications and to allow a simple development of similar systems in fusion facilities and in other applications.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission

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Non-fusion Applications

HTS-FPs can find application in sectors involving high-current superconducting magnets to be supplied at low voltage in persistent or quasi-persistent mode. The energization of superconductors, with a special emphasis on HTSs, is acknowledged as a major technical challenge also in other applications where they are employed or expected to be introduced, like electrical machines (superconducting motors or generators), power-dense lightweight wind turbines, particle accelerators, high-field nuclear magnetic resonance (NMR) systems, superconducting electric thrusters for satellites, and even novel concepts of gantries for hadron therapy, like the Gatoroid.

EUROfusion Heritage

The state-of-the-art systems used to power superconducting magnets in nuclear fusion devices are bulky, causing significant power losses as well as disturbances, harmonic pollution, and reactive power flows in the electrical grid. Current leads that transport current from room temperature to cryogenic temperature represent one of the main sources of thermal loads for the cryogenic system. Additionally, the busbars required for connecting the magnets to the power supplies require a large footprint, complicating layout and assembly, and causing significant power losses at room temperature. All the aforementioned challenges are significant drawbacks and represent threats to the feasibility and cost-effectiveness of future magnetic confinement fusion reactors. As ENEA is among the partners of this technology proposal, the validation of the technology for fusion applications could be achieved in the Frascati Coil Cold Test Facility, thus bringing a significant innovation and impact in the fusion industry. The benefits of a HTS-FP-based solution would be relevant for a medium-size experiment like DTT, but would be even more significant for future long-pulses superconducting fusion machines, such as DEMO, where the operations of the TF magnets are very long and persistent and where the dissipations must be minimized to optimize the produced net energy.

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