Abstract

Nuclear fusion is widely regarded as a promising solution for future clean energy production. As a process, nuclear fusion is inherently carbon-free and generates minimal long-lived radioactive waste, making it an attractive alternative to traditional energy sources. In recent years, there has been a surge in both public and private investment, reflecting the growing global interest in harnessing this technology.

However, despite this increased investment, controlled nuclear fusion remains a big engineering challenge. Significant issues still need to be solved before this technology can be successfully implemented in commercially viable power plants connected to the grid.

Among these challenges, a critical aspect is achieving optimal plasma confinement within the fusion reactor. Magnetic confinement appears to be the most promising approach. This method relies on the interaction between charged plasma particles and a carefully designed magnetic field. This field, typically with a helical shape, confines the plasma within a toroidal chamber. To build such a magnetic field, two main technological solution are proposed: the tokamak and the stellarator. In both the cases, due to the very high magnetic field and transport current, superconductors are used to wind the coils, to avoid Joule power losses within the winding, which would be excessive using normal conducting materials. If the use of superconductors enables the possibility of increasing the magnetic field and the transport current, it introduces additional complexity, since the superconductors must be kept within their critical surface, while preserving their mechanical integrity. To design such magnet system it is of key importance to rely on numerical models which are able to consider all the different relevant physics involved. In this work, an integrated platform for the multi-physics simulation of such superconducting magnet system has been developed, including thermal-hydraulic,

electromagnetic, electrical and mechanical aspects. The thermal-hydraulic analysis is the core and starting point of the developed platform and is based on the state-of-the-art 4C code, developed at Politecnico di Torino, since the early 2000s. On top of the thermal-hydraulic code, other physical models have been developed starting from the electromagnetic one, namely the 3D-FOX, which is an open source 3 dimensional finite element code for the evaluation of eddy current power deposition in the coil conductive components, which is a key heat load to be considered in the thermal-hydraulic analyses.

Another quantity which is fundamental to be properly evaluated to obtain self-consistent and reliable results is the coil current evolution, which influences both electromagnetic and thermal-hydraulic aspects. For this purpose an electrical system level model (called "4C/DC") has been developed aiming both at computing the coil transport current on the base of the power supply system design, but also the winding pack current distribution in case of non-insulated or partially insulated coils. Such results becomes inputs to both the 4C code and the 3D-FOX.

Eventually a mechanical model, called MECHANO (Coils MECHanical ANalysis tOol), has been developed, ranging from the cable to the full coil level, with the main objective of analyzing the impact of temperature distributions on the mechanical integrity of the cable or coil in normal and off-normal conditions.

Particular focus has been dedicated to the the coupling strategy between the various models developed, aiming at optimizing the computational cost of the analysis while preserving the accuracy of the computation. Models have been connected in series (run sequentially) when the feedback between the physics is mainly one-way. Whenever this assumption can not be done, continuous connection between the models at runtime (online co-simulation) is required; in this work this connection has been guaranteed through the FMI standard.

Eventually some application of the simulation platform developed here are presented aiming at showing the important contribution that the multi-physical modeling gives in support to the design of optimal superconducting magnet system for nuclear fusion reactors.

In perspective, important validation campaign is foreseen for the newly developed model, which has been, for the time being, only verified and benchmarked against analytical formulations or against other commercial codes.