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DEVELOPMENT OF AN AUTOMATED HIGH TEMPERATURE SUPER-CONDUCTOR COIL WINDING MACHINE AT CERN

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Abstract

Within the framework of technology studies on future accelerators, CERN has initiated a five-year R&D project aimed at the evaluation of REBCO (Rare Earth Barium Copper Oxide) High Temperature Superconductors (HTS). The study covers a number of areas from material science to electromechanical properties. The REBCO high-field tape will be tested on different HTS magnet prototypes, such as HDMS (HTS Demonstrator Magnet for Space), GaToroid (hadron therapy Gantry based on a toroidal magnetic field) and other smaller coils that will be fabricated to study the tape's potential. To assemble the HTS coils, a new automatic winding station has been designed and constructed at CERN. A touch panel combined with embedded controller, running software developed in-house provides a sophisticated, yet intuitive and user-friendly system aimed at maintaining perfect coil winding conditions. In this paper, we describe the mechanical choices and techniques used to control the seven HTS spool tapes and the winding machine. We also present the analysis of several coils already produced.

INTRODUCTION

Whether for the next generation of high energy particle accelerators, or for the development of new equipment dedicated to physics or medical research, one of the main decisive factors in the future will be the industry's ability to produce superconducting magnets with a field of at least 20 T [1].

Being one of the world leaders on superconducting magnet technology, CERN has been given responsibility of work-package 10 (WP10) "Future Magnets" as part of their contribution to the EuCARD-2 project [2], supported by the European Commission's Seventh Framework Programme (FP7). WP10's main goal was to manufacture and qualify an HTS cable, within real demonstrator coils and magnets, having useful characteristics for accelerator magnets (dipole field of 20 T, industrialized production, affordable cable, …).

After studying several possible candidates, the REBCO tape was chosen as an appropriate candidate, mainly because of its mechanical properties, but also due to its availability through many different suppliers, and finally because it doesn't require any further treatment before assembly [3].

In 2017, the ARIES European program was launched with the objective of improving the REBCO tape current density [4]. In parallel, CERN initiated a 10-year research program (CERN HTS program) to study and develop dipole magnets with magnetic fields beyond 20 T [5].

The Prototypes and Demonstrators

To test and evaluate the new requirements, several R&D studies were launched, each focusing on different technologies.

- The HTS demonstrator magnet for space (HDMS) aims at validating the feasibility of a new generation of magnet to be used for a spatial spectrometer [6].
- The 20 T HTS Clover Leaf End Coils magnet to study the mechanical and magnetic aspects of so-called overpass / underpass coil end assembly [7].
- The 8.2 T toroidal coils, which would be the basis of the GaToroid CERN proposal, for a new gantry design in the field of Hadron cancer treatment [8].
- The small coils program as a general study of high-field accelerator magnets for Hadrons and Muons (solenoid, undulator) [9].

The Coil Winding Machine

In order to co-wind stacks of REBCO tapes, dedicated tools and custom machinery is needed for its assembly. It was therefore decided that the coil-winding machine would be built in-house, at CERN. As a result, different teams involved in anything from magnets design, mechanical studies to control system development, joined forces to manufacture and assemble the machine in just a few months [10].

THE WINDING MACHINE DESIGN

One of the main requirements of the machine design was the semi-automation of the winding process to be capable of working with up to 7 tapes simultaneously. An important request was the ability to set up and control in a closed loop the tension on the spools, with added monitoring and storage of the results.

The winding station was built as a long table made of aluminium profiles with 7 spools, each connected via a clutch to a dedicated motor (Fig. 1). Next to the spool holder, custom-made tape routing equipment was installed, both guiding and measuring the tension applied to the tapes. In addition, tape alignment tooling with a built-in length encoder was incorporated into the machine to merge and adjust the tape position before winding the coil.

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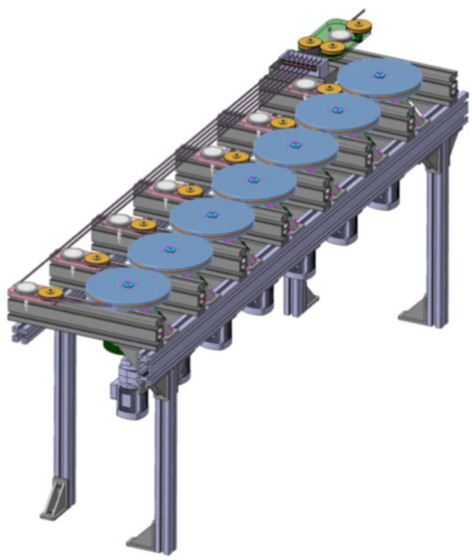

Figure 1: Winding station 3D model.

THE CONTROL SYSTEM

After assembling the winding station, the decision was made to build and develop a control system using a CompactRIO [11] controller from National Instruments, taking advantage of its combined RT-FPGA nature, and also because some machines hosted in the workshop had already been successfully renewed with this solution. To allow easy and intuitive human-machine interfacing, a Windows based touch panel was added to the system, allowing the user to constantly monitor the winding process parameters, as well as reconfigure regulation coefficients.

Early in the control system design phase we realized that even minor abnormalities in the operation might have critical impact on the components and the winding process product itself. It was clear that maintaining perfect tension conditions (7 – 100 N) of REBCO tapes would be key to the performance of the manufactured coil.

During the initial design, three important aspects were identified. First, the controller is supplied with quarter bridge strain gage inputs and AO voltage modules. Second, gage signals are used as process variables of the PID regulation loops, running on the embedded FPGA, while the outputs operate as a source (0 – 10 V range) to control the clutches. Third, the cRIO controller also handles DIO signals, connected to the motor relays, safety system buttons and encoders (Fig. 2).

A logging option was added to keep track of parameter changes. These are stored in a file referenced to the manufactured coil for future quality insurance assessment.

Mechanical Control of the Spools

When the machine is running, only the clutch is actively controlled, while both the gear and the motor are statically configured. This makes it possible to control the final torque, speed and cable tension by regulating the clutch. Due to safety-related aspects, the station is designed to disengage power transmission when idle. The clutch is controlled proportionally with a current between 0 and 2A, allowing active control of the spool.

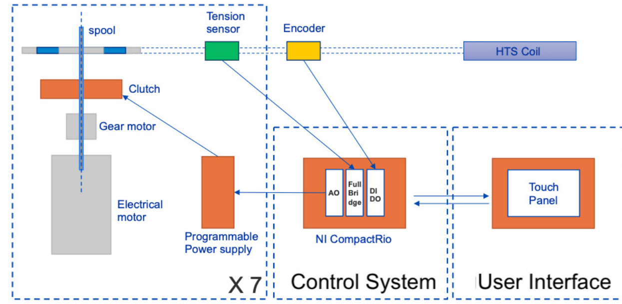

Figure 2: Mechanical diagram of the machine.

Sensors

One important factor when choosing suitable tension sensors is their readout range. Those selected for the assembly have slightly higher limits than required (200N), but one must consider their location in reference to the spools. As the point of contact between the cable and the strain gage pulley is rotated by 45° relative to the pull direction, the real maximum value of the tension that can be read on the tape is closer to 140N. This value can be adapted by orienting the sensor differently.

The Embedded Controller

The cRIO-9053 controller used for the project has proven to be a good choice in terms of its price/capability ratio. Our optimizations, such as pipelining and reduction of critical paths, allowed us to implement the software in a relatively small FPGA.

Software Architecture

Since the final implementation of the winding machine was not completely defined when the project started, we had to choose a flexible yet scalable software architecture that could easily be adapted to changing project requirements.

The software was developed using an optimized QMH (Queued Message Handler) software architecture. By offloading most resource-consuming tasks such as PID calculation to the FPGA, and by running the GUI on an external Windows based touchscreen-enabled computer, we managed to fit the application on the RT controller.

The FPGA Application

An FPGA-based firmware executes the most critical and time-consuming calculations related to the PID algorithm as well as direct hardware interfacing. Of seven parallel processes, three of them are related to regulation. Even if coil winding is a relatively slow process, the stable clocks of the FPGA tasks allow them to react very quickly to any change in the tape's tension by running the main loop with a cycle time of a few milliseconds.

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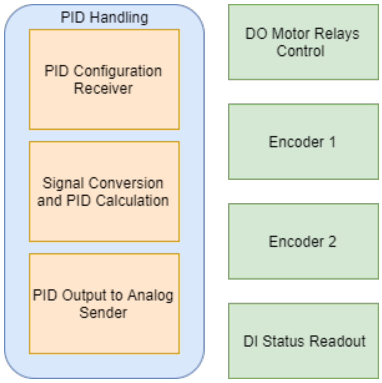

Figure 3: FPGA application parallel processes.

The FPGA implementation is divided into 3 main processes (Fig. 3). The First process is mainly dedicated to configuration management and parameter updates. The second process performs low-level signal calibration and conversions and stores calculated PID outputs into memory blocks. Finally, the third process reads control variables from memory and writes to the analogue and digital output modules.

Thanks to this modularized approach, the code is compartmentalized and simplified, preserving high configurability (fragments of program logic can be disabled or supplied with simulated parameters instead of real ones).

GUI and User Interaction

The main challenge when implementing a graphical user interface for the project was to keep it simple enough to ensure clear understanding of the machine status, yet deliver a fully functional tool to the operators. This was made even more difficult considering the low resolution and relatively small size of the touch-panel (Fig. 4). Ultimately, close cooperation with the operators and an iterative approach to development paid off with satisfactory results. The user interface is split into three panels (Fig. 5): Operator settings, runtime monitoring view and expert settings.

Figure 4: Winding machine with touch-panel user HMI.

The first panel consists of elementary winding process configuration, where the user needs only to specify tapes and tension to be used, in addition to optional informational values like operator or coil name.

The second tab provides run-time information and controls. In the central part, the application plots the current tension on a graph while on the left there is an adjustable set point indicator. This way, the user can perform slight tension adjustments during the winding process. The lower part of the GUI is reserved for the encoder readings (they are used to track used tape length and coil layers achieved). Two registers are kept for each encoder: temporary and total reading. The former resets on operator request and the latter is cleared only on winding process start-up. From this panel, the operator can start and stop regulation.

The "Expert Settings" panel is meant to be used only by experienced engineers to modify PID, sensor calibration and debug functionality. This tab is also password protected as because using these options by non-qualified users could damage the coil and REBCO tapes. A final feature from this panel is the live monitoring of some key electrical elements, like the power supplies, the safety stop relay and the motor contactors.

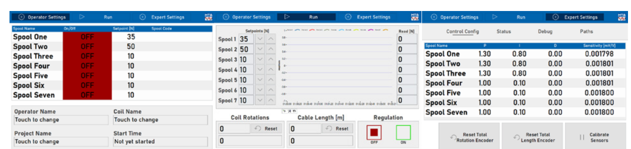

Figure 5: Application GUI.

PID Regulation

The coefficients of the PID regulations were first estimated, based on a theoretical approach. Then by using a spool of a few meters of copper tape, we adjusted them by executing dozens of tests of the regulation loop. During this process, some mechanical changes were made for the position of the strain gages and the pulleys. Following the final acceptance of the mechanical assembly of the machine, a test campaign was executed with 7 spools of copper tape during which the complete regulation loop was fine-tuned (mechanical, electrical and software parts).

COIL PRODUCTION RESULTS

Since 2020, the winding machine was used to produce HTS small solenoid, Undulator, HDMS, and Gatoroid coil prototypes. The currently produced pieces have been evaluated and mechanical parameters were assessed to improve the winding processes. Many trials were performed with partial winding of these coils and iterations of the assembly protocol, conducted to validate most of the coil prototypes production steps.

The Solenoid Coil

The first prototype (Fig. 6) was made using copper tape. It allowed us to validate some steps of the coil assembly:

- The tape tension (30 N)

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- The soldering process of the first turn on the copper ring support (before the winding)
- Soldering paste and heater device (T = 176° C) between each turn

Then the next prototypes were wound on another machine, as the seven spools winding machine was occupied by other projects (HDMS/Gatoroid).

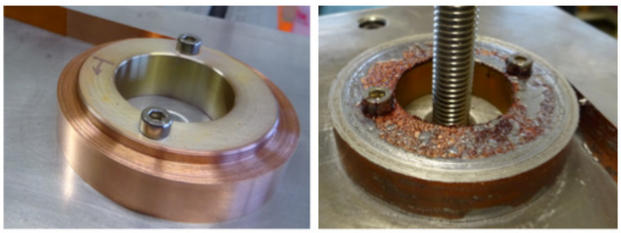

Figure 6: a) Solenoid coil winding, b) Soldering paste deposit.

The Undulator Coil

The winding machine was used to produce the very first vertical racetrack (VR) coil prototype [12], with two 4 mm copper tapes (Fig. 7). The simultaneous winding of two tapes was validated, but the distribution of the solder in between tapes was not uniformly distributed as needed. It was decided to wind the following prototypes in a vertical winding orientation, which was possible on another winding machine already present in the workshop, which was adapted for this purpose.

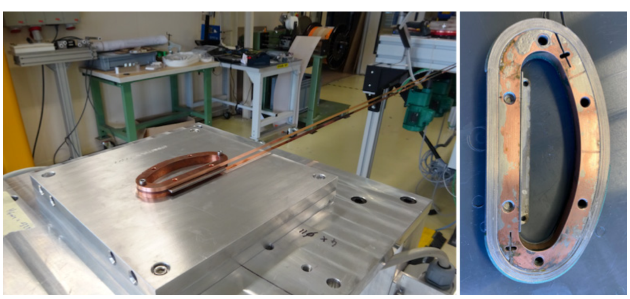

Figure 7: a) Winding of the first VR coil, b) The final coil after the soldering process.

The HDMS Coil

Five coils were made with the winding machine. Only the third and the fifth did not have geometrical errors. Finally, only the fifth one was retained to validate the winding process, using three copper tapes 12 x 01 mm, with an applied strain of 20 N on each. Several steps of the HDMS coil assembly (Fig. 8) still need to be tested (last turn fixing method, …) or studied (external copper ring to maintain the coil) but this is beyond the scope of the winding machine.

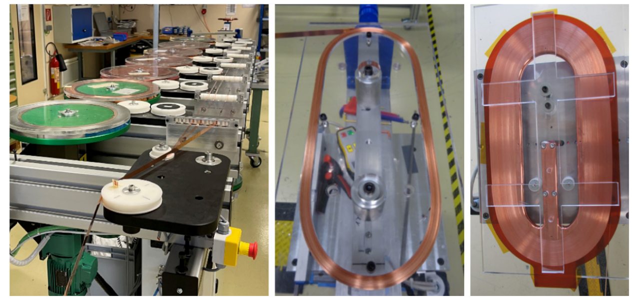

Figure 8: a) The winding machine with the 3 tapes, b) The HDMS coil winding, c) The complete coil.

The Gatoroid Coil

A first trial was done with this assembly scheme: six copper spools installed on the winding machine (1 x 0.5 mm, 4 x 0.1 mm, 1 x 0.5 mm). Several winding iterations permitted to get the optimal strain to apply on the tapes (50 N on 0.5 mm, 30 N on 0.1 mm). A second trial, using an S-2 fiberglass sleeve, was done to validate the insulation between the layers (Fig. 9). This also confirmed the tension and trench geometry for the coil support. A new mount for the fiberglass sleeve was added to remove friction at the entry point. The assembly process of the second layer spools was also validated by adding a second winding station, made of one axis and six spools. The six tapes were passed through the insulations and were again separated into six independent spools in the winding machine.

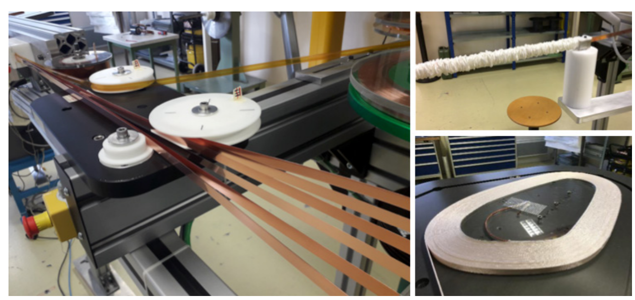

Figure 9: a) The winding machine with the 6 tapes, b) The S-2 Fiberglass stored on the tapes path, c) The Gatoroid coil.

CONCLUSION

The production of the first batches of coils showed that the winding machine works properly. Considering our broad experience with the NI ecosystem, time-constraints, and the robustness of FPGA based solutions, a CompactRIO controller was a clear choice as a basis for the control system. The complete control loop, from the strain sensors, the FPGA running the PIDs, up to the clutches is now set up with very good accuracy. Some mechanical parts have been reengineered during the test and validation campaign (position of pulleys in the merged tapes area, space between pulleys, orientation of the strain sensors). The GUI has been improved to offer more features during operation (easy control settings from the RUN panel, logging of all the commands for future support cases investigation). The winding machine now provides

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an efficient service for the production of HTS coil prototypes at CERN. The possibility to wind and unwind a coil gives freedom in using copper tapes (less expensive), for process validation purposes.

FUTURE PLANS

The validation and initial tests of some winding processes have uncovered needs for mechanical improvements. Several new modules are being designed for some specific phases of the coil winding, such as new fiberglass sleeve storage and mounting system, a thermoforming device for the polyimide insulation thin film layer, and a new dimensional measurement control system for the respooling phase.

On the control and software side of the winding machine, some new features are already planned for better management of the HTS tapes inventory. The idea is to link the GUI with a database to get tape identification and parameters. This will be done by scanning a QR code on the spools to then import automatically the associated properties from the database. This will improve the QA and traceability of the produced coils, by saving tape characteristics with the data generated during the assembly. At the end of the process, this data will be archived in the database. The lengths of used tapes will also be automatically updated to allow an accurate management of available stocks.

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