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Development of a Tape Winding Mechanism for HTS Power Cables

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Abstract

Manufacturing of HTS power cables requires winding the HTS tapes helically around a former. These HTS tapes are costly, and delicate and require sophisticated winding machinery which is expensive. In this paper, an in-house economic mechanism for converting a conventional lathe machine to a Tape Winding Mechanism (TWM) is discussed in detail. In addition to the developed prototype, the technical issues and challenges encountered during the development of TWM are listed. The developed TWM was instrumental in successfully winding 10 HTS tapes simultaneously around a tin-coated braided copper former of 19 mm diameter with a pitch length of 210 mm for a continuous length of 5 m HTS cable. The recommendation of modifying any existing cable winding machine to TWM is also discussed.

Keywords: HTS Power Cables, HTS Tapes, Pitch Angle, Pitch Length, Tape Winding Mechanism

1. Introduction

High Temperature Superconducting (HTS) power cables are being developed all over the world[1-3], and they have the potential to completely transform the conventional power transmission sector. The Indian Institute of Technology, Kharagpur is currently working on a 5 m HTS power cable with an 11 kV and 1 kA rating. Both AC and DC excitation will be used to test the cable.

The cable core consists of a tin-coated braided copper rope which acts as a former. The HTS tapes are wound helically onto the former after which a semiconducting layer is wrapped around the HTS tape layer followed by the cold dielectric (PolyPropylene Laminated Paper). A schematic of the single-phase HTS power cable being developed is shown in Figure 1.

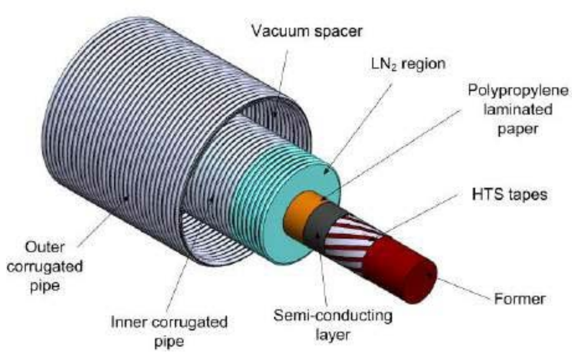

Figure 1. Schematic of single phase HTS power cable.

The HTS tapes are multilayered composites in which a Rare-earth Barium Copper Oxide (ReBCO) layer is deposited on a substrate which acts as the superconducting layer and offers zero resistance for DC excitation. In addition, there are copper and silver layers which act as stabilizers to provide necessary structural reinforcement, enhance thermal conductivity and also provide dynamic stability during the quench.

The schematic and thickness of the different layers are shown in Figure 2[4]. The ReBCO layer is a brittle ceramic material that must be handled with caution because excessive stresses can cause irreversible damage to the tape's layered structure. Investigations have been reported on the deterioration of I-V characteristics of HTS tapes under tensile stress[4]. Therefore, the tape winding mechanism using HTS tapes is different from the manufacturing of conventional copper or aluminium wire ropes.

In the commercial market, several wire winding mechanisms are used to manufacture various wire ropes such as braided wire, single layer, Seale, filler wire, Warrington, combined patterns, and for other

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Figure 2. Schematic and thickness of different layers of an HTS tape.

applications such as insulation winding[5–7]. During the winding of copper/aluminium strands for wire rope making the amount of force applied during fabrication is very high and is isotropic. Applied forces consist of torsion, shear, radial compression and axial tension which results in the permanent deformation of the wire strands. This, however, does not impact power transmission efficiency. However, the same winding mechanism cannot be adopted for making an HTS power cable because the HTS tapes have non-isotropic geometry as well as internal structure. This non-isotropic characteristic of HTS tape influences the performance of the HTS cable, therefore, special care in the fabrication procedure and mechanisms are required to be adopted for the fabrication of HTS power cables. The winding mechanism for HTS tapes becomes more complicated as the length of the cable increases due to multiple tape handling, tape twisting, overlapping and breaking. These physical constraints are required to be addressed for modifying the existing cable winding machinery for HTS TWM. In addition, the fabrication of HTS cable is not common concerning the existing conventional power cable; hence, investing a large amount of money in setting up a new HTS TWM is not economical. However, minor modifications in the existing cable winding machinery can lead to an economical solution which can be adopted by the cable industry for manufacturing long lengths of HTS power cables.

The issue of handling multiple tapes and twisting HTS tapes can be addressed by using a suitable tape guiding mechanism. The other issue of overlapping can be resolved by selecting suitable pitch angles and pitch lengths along with an adjustable tensioning mechanism to avoid slacking of HTS tapes during winding around the former. The tape tensioning mechanism often results in scratches over the HTS tape surface which may affect its performance and at times also results in the breakage of HTS tapes. These issues can be eliminated by providing suitable width dimensions to HTS tape spools and incorporating cushions in the tape tensioning mechanism. To demonstrate the prototype for the developed conceptual design, it was decided to use an existing lathe machine (available at IIT Kharagpur) to aid in the winding mechanism. In this paper, the complete procedure and cable winding design mechanisms are discussed.

The objective of this work is to design, develop and test an indigenous, economic, lab-scale winding mechanism to fabricate HTS cables using HTS tapes. Section 2 describes the design mechanism and development of HTS TWM. Section 3 describes the calibration procedure of TWM. Section 4 discusses the procedure for the operation of TWM whereas Section 5 summarizes problems and the solutions encountered and adopted during the design and prototyping of TWM.

2. Design Mechanism and Development of Tape Winding Mechanism

The TWM was designed based on the need to simultaneously wind 10 HTS tapes on a former with a desired pitch length and a pitch angle of 210 mm and 15.850 respectively.

2.1 Specification of HTS Tapes and Sizing of Conductor

Based on the rating of the HTS cable being developed (11 kV, 1 kA), it was decided to use 2G HTS tapes supplied by SuNAM as the superconducting element. The

Table 1. Specifications of HTS tape- SuNAM (SLBS04150)

Parameter	Value
Width (mm)	4.4±0.2
Thickness (µm)	290±30
Tc (K)	91
Critical current (A)	>150
Minimum double bending diameter (mm) (95% Ic retention, room temperature)	30
Maximum rated tensile stress (MPa) (95% Ic retention, room temperature)	>250

specifications of the selected tape are shown in Table 1. The specifications include the dimensions, the minimum bending diameter and the maximum tensile stress affecting the handling of HTS tape during winding.

The dimensions of the former and the subsequent layers including the HTS tape, semi-conducting and PolyPropylene Laminated Paper (PPLP) layer are shown in Figure 3. The number of HTS tapes required was calculated to be 10 for a current carrying capacity of 1 kA.

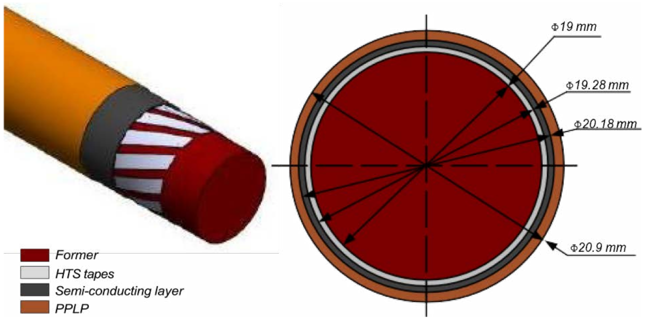

Figure 3. HTS cable core layers and dimensions.

2.2 Design Steps and Components

The steps involved in the design of the TWM are shown in Figure 4. Once the dimensions of the former and the number of HTS tapes to be accommodated on the former are determined, the next step involves the sizing of the individual spools which will hold the individual tapes to be wound. The spools were made of transparent acrylic sheets to observe the behavior of the tapes during winding and unwinding on the spools. As it was decided to use a lathe machine, the next step involved is the positioning (angle and height adjustment) of HTS tape spools around the lathe chuck. In addition, the former has to pass through the centre of the lathe chuck through a size Poly Vinyl Chloride (PVC) guide pipe with an inner diameter of 25 mm pipe. The length of the pipe is chosen such that it supports the former from the tape guide to the headstock of the lathe machine as shown in Figure 6. Additionally, the spools were held together on a wooden base and were positioned using adjustable brass spool holders and stands.

To prevent the tapes from overlapping and becoming slack, a tightening mechanism consisting of wedges lined with felt was used. The felt lining protects the surface of the HTS tape from scratches due to friction. Lastly, a tape guide made of Teflon was provided to carefully guide the HTS tapes to the former surface. The tape guides have

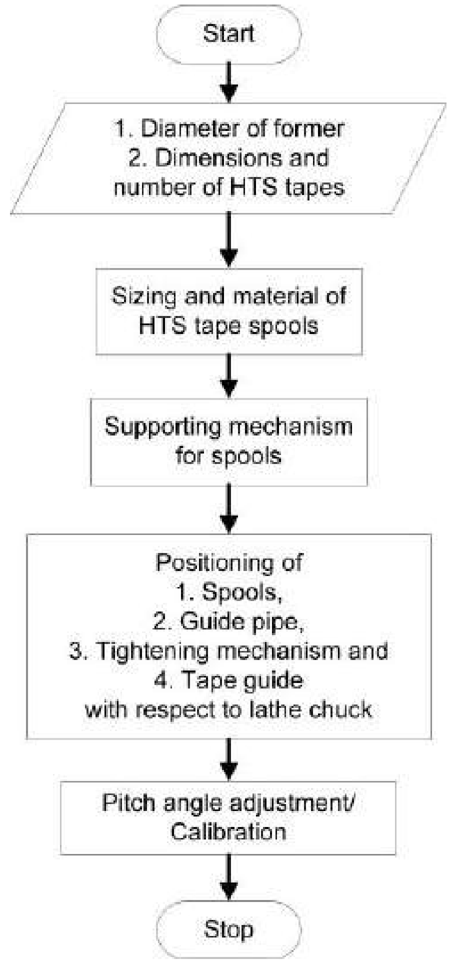

Figure 4. Flowchart for designing tape winding mechanism.

slots adjusted at an angle of 15^0 to avoid the twisting of HTS tapes during the winding procedure. The list of the components is shown in Table 2.

A three-dimensional Computer Aided Design (CAD) model of the assembled TWM is shown in Figure 5. The photograph of the fabricated assembly mounted on the three-jaw chuck of the lathe machine is shown in Figure 6.

Table 2. Components of the winding mechanism

Part name	Material	Qty.
Base	Wood	1
Spool holder	Brass	10
Tightening mechanism	Felt, SS bolts and nuts, Perspex	10 sets
Spool	Transparent Acrylic sheet (Perspex)	10
Spool stand	Brass	10
Tape guide	Teflon	1
Pipe	PVC pipe	1

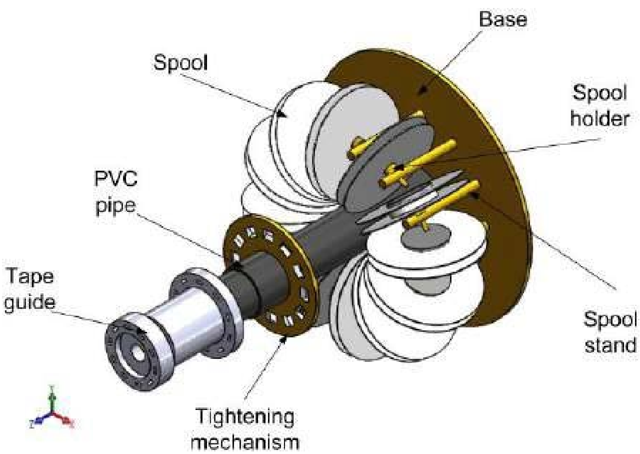

Figure 5. 3-D CAD model of spool holder and guide.

3. Calibration of Chuck, Lathe and Tool Post of TWM

Since the winding pitch selected was 210 mm, the chuck has to be rotated 360^0 for an axial cable length of 210 mm. This corresponds to a chuck rotation of 45^0 for the tool post travel of 27.5 mm.

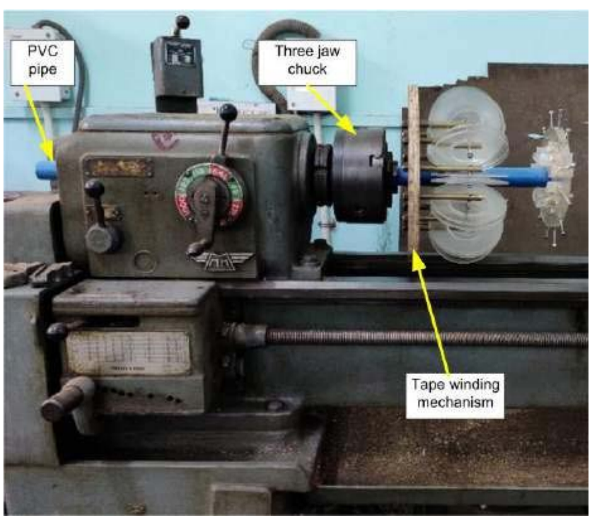

Figure 6. Photograph of lathe machine and tape winding mechanism.

Thus, a calibration procedure was adopted where the markings were made on the lathe chuck and bed (base of tool post) as shown in Figure 9.

4. Winding Procedure

To test the working of the developed tape winding mechanism, it was decided to first test the mechanism initially using ribbons. The successful demonstration led to a trial using copper tapes. Finally, once it was proved that the concept and the execution were possible, it was decided to wind the HTS tapes on the former. A flow chart explaining the winding procedure is shown in Figure 7. The procedure followed is given below:

The tape winding mechanism was positioned in the chuck of a lathe.

- The HTS tapes were cut into 10 strips of 5.5 m length each and were wound on the HTS tape spools.
- The HTS tapes at the end have to be fixed to the copper braided wire rope. However, soldering them directly may damage them due to the high temperature of the soldering process. Thus, the HTS tapes were individually soldered to 10 separate copper tapes (as shown in Figure 8).
- The tin-coated copper former in the form of braided wire rope was passed through the end of the lathe chuck.
- The HTS tapes from the HTS tape spool were made to pass through the tightening mechanism and the tape guide.
- The copper tapes were soldered to the former.
- This soldered end was then fixed using a pinching mechanism on the tool post.
- Both the chuck rotation and the tool post-travel were done simultaneously to ensure uniform winding of the HTS tapes.
- After around 0.25 m of tape was wound on the former, semi-conducting tape was wound on the wound HTS tapes. Apart from the function of smoothening the electric field during operation, the semi-conducting tape holds the HTS tapes together to the former and prevents them from unwinding.
- Once the tool post reaches its travel limit, the pinching mechanism was loosened and the tool post was brought back to its original position (near the chuck).
- It was then engaged again and the procedure was repeated till the HTS tapes on the spools were completely wound.

The photographs at the commencement of the winding procedure and the cable core after winding are completed, are shown in Figures 9 and 10 respectively.

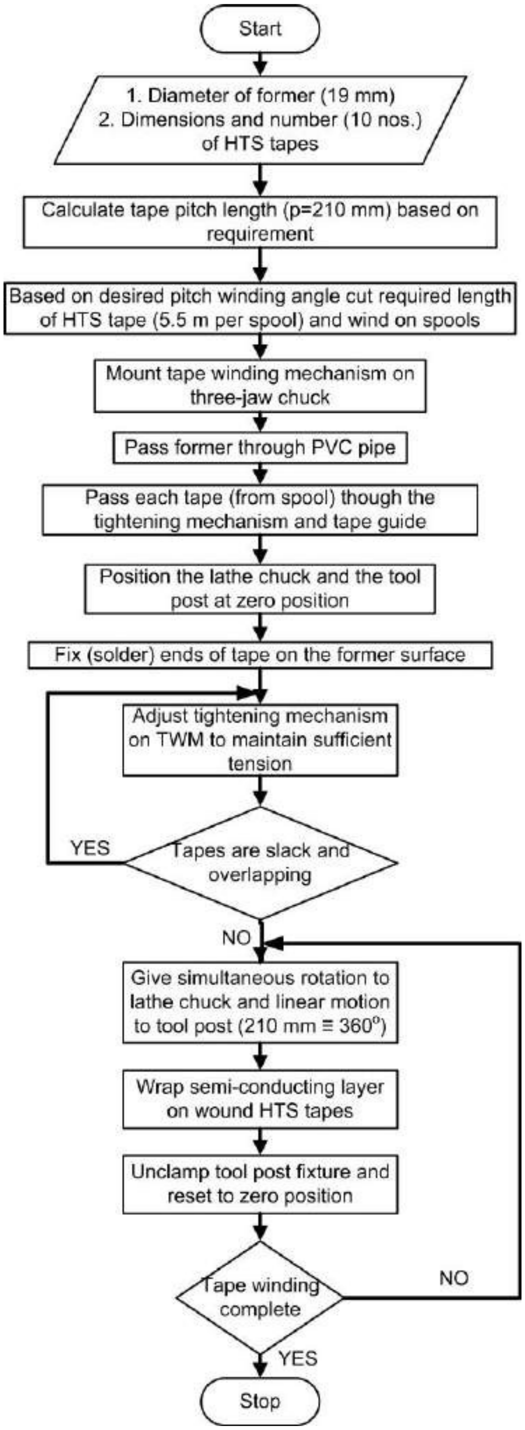

Figure 7. Flow chart for tape winding procedure.

5. Problems Faced and Solutions

Initially, soldering the HTS tapes directly onto the former proved to be difficult. Also, the former (having a high thermal mass) had to be warmed for a long duration at an elevated temperature. This resulted in damage to the

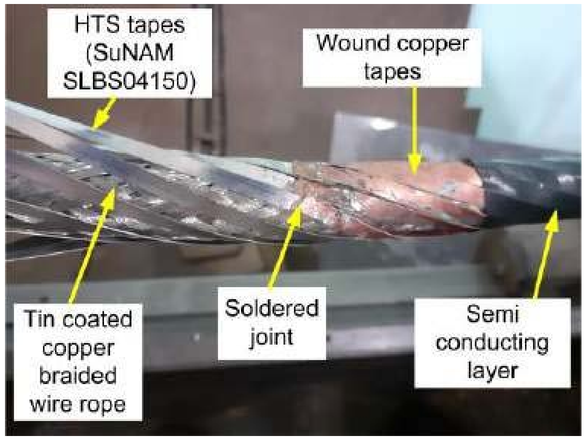

Figure 8. Photograph of the soldered joint to join HTS and copper tapes.

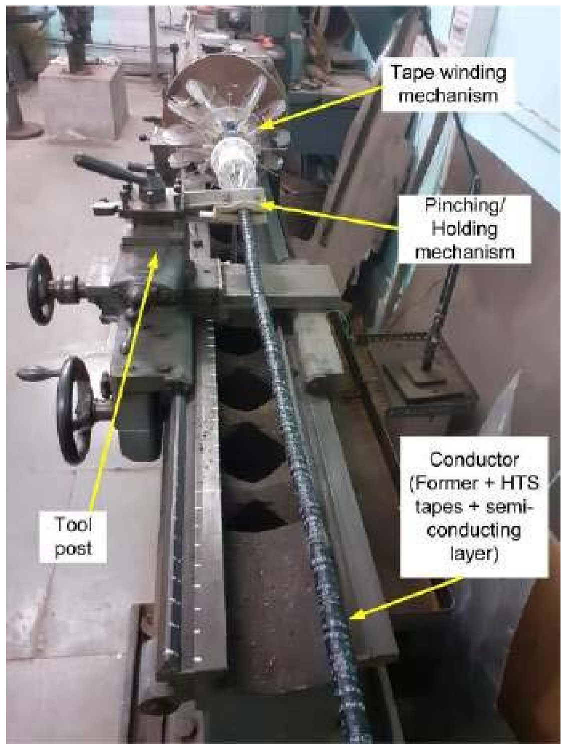

Figure 9. Photograph of an end view of cable core after winding.

costly HTS tapes. This problem was tackled by soldering the HTS tapes to copper tapes of similar dimensions which were relatively easier as shown in Figure 8. The copper tapes were then soldered to the former.

During the trial with the copper tapes, it was observed that the tapes were slack and this resulted in overlapping. To avoid this problem a tightening mechanism, as shown in Figure 11, was used along with a tape guide (Figure 10).

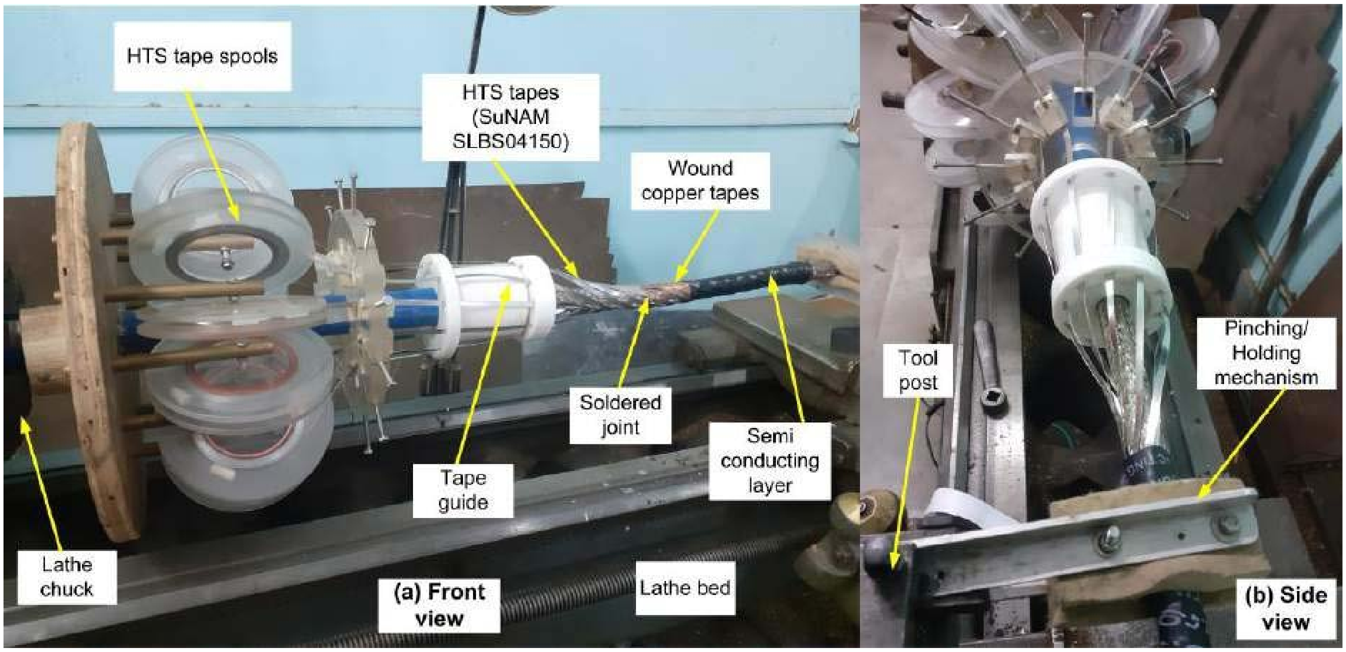

Figure 10. Photograph of front and side view of cable core during winding.

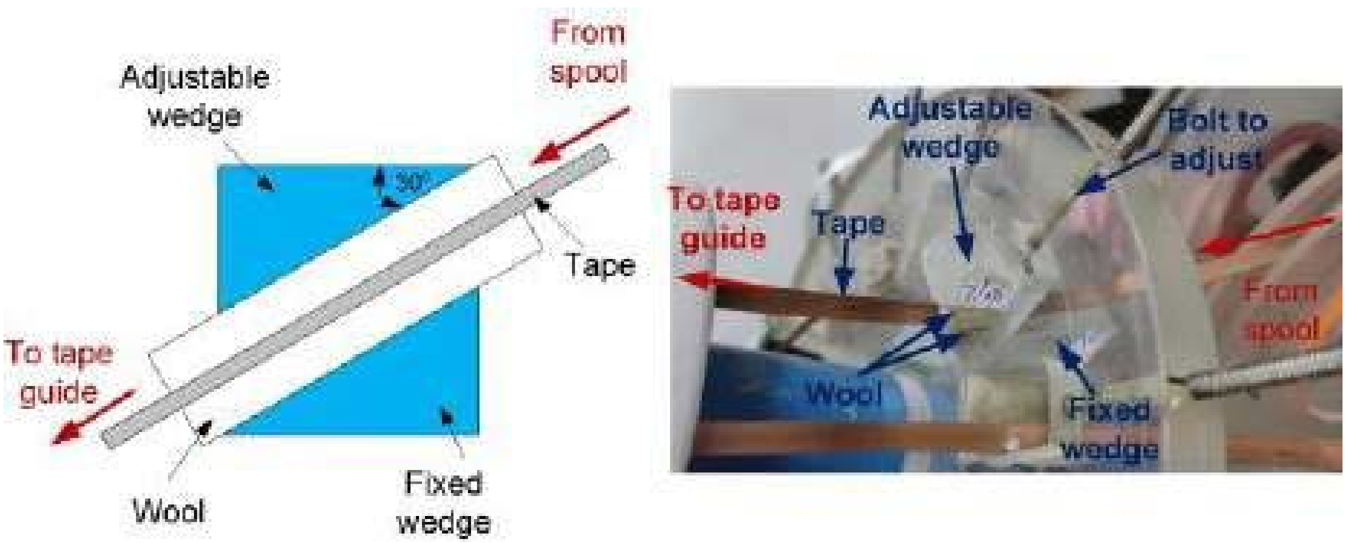

Figure 11. Cross-sectional view and photograph of the tightening mechanism.

The tension in the tapes can be adjusted by tightening and loosening the bolts on the tightening mechanism. Wedge-shaped perspex pieces were used to guide the tapes by an angle of ~30^0 and felt was used to cushion the tapes thus preventing scratches on the HTS tape surface due to friction between the tape surface and the wedges.

The lathe chuck holding the TWM was manually rotated by hand while the tool post pulling the cable former was also manually given a linear motion. However, for a cable with a long length, automation may be incorporated to control this combined motion. This may be done by using the worm (lead screw of the lathe) and worm wheel which are often used for threading operations.

The 10 HTS tapes were wound around the former having a diameter of 19 mm with a pitch length of 210 mm. The resultant pitch varied between 205 to 215 mm which results in an accuracy of ~2.4 %.

6. Conclusions

The design steps along with details of the components fabricated to develop the TWM for HTS cable manufacturing are shared. The procedure to helically wind 10 HTS tapes on a 19 mm former with a pitch length of 210 mm has been explained in detail. This same mechanism may be used even when the required pitch length changes.

Ten HTS tapes were wound around the former having a diameter of 19 mm with a pitch length of 210 mm to an accuracy of ~2.4 %.

Existing TWMs consist of components such as spools, supports and the rotation mechanism; however, due to the delicate nature and cost of the HTS tapes, the required modifications including the tightening mechanism and the tape guide have been explained. This conceptual prototype is the basis for minor, cost-effective modification of any existing TWMs such that they may be used to wind HTS tapes.

The developed TWM was instrumental in realising India's first 5-metre HTS power cable, rated at 1 kA and 11 kV.

7. Acknowledgment

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8. References

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