Chapter 5: Conclusions & Future works

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Conclusions:

A finite length of YBCO high temperature superconducting strand has been subjected to a disturbance in the form of a finite heat put with isolated boundary conditions similar to conduction cooled devices. A mathematical model of this operating scenario has been developed. The analyses show that high temperature YBCO tape with uniform surface temperature prior to the application of the disturbance quickly loses cryostability. However, the temperature remains stable at the centre of the tape. The unstable edge region of the tape shows a raise in bulk temperature trying to equilibrate for a given heat input. The temperature instability propagates towards the center as time progresses. These results reaffirms the fact in cases of superconducting tape of finite length at LN$_2$ temperature subjected to an unforeseen thermal instability, the edges requires adequate cooling. This additional cooling prevents the development of hotspots and local non-uniformity of transport currents. These measures in practice can lead to avoidance of quenches.

In similar fashion, a three-dimensional heat conduction model from first principles, for YBCO wire of finite length as well as very long length have been established for forced flow cooling scenarios. In the case of YBCO wire of finite length, the temperature of the wire exhibited rapid increase at the edges as well as at the outer surfaces. Subsequently, the temperature front propagates radial inwards towards the core. In order to maintain the superconductivity behavior in the forced flow cooled strand, more efficient continuous cooling are mandatory at the edges. In cases of strands of long length, the temperature behavior depends on the heat transfer coefficient. With higher heat transfer coefficients, the wire quickly attains the surrounding temperature. Thus, in practice, it is recommended to have the cooling mechanisms with enhanced heat transfer coefficients in a forced flow scenario. Such enhancements of heat transfer coefficients are feasible with improving the mass flow rate of coolant, improving wetted perimeter and so on. In cases of spatially distributed transients, a sharp temperature rise of the conductor temperature is observed irrespective of the heat transfer co-efficient. Cooling towards such transients is not feasible but adequate measures must be taken to enhance the
transient heat transfer coefficients in such situations. The transient heat transfer coefficients are enhanced by avoiding films on the wetted surfaces.

Next, a detailed mathematical analysis of the temperature profile evolution following a quench in a HTS has been carried out. For a finite length YBCO state-of-the-art high temperature superconductor, the threshold quench energy is around 12.8 J/m when averaged over the overall tape dimension (10 × 0.4 × 0.02 cm). On the superconducting film section, this energy is about (0.8 μm thickness) is 0.0512 J/m. However, the energy margin of 12.8 J/m is relevant here as the heat capacities of the matrix and stabilizer materials take a major role prior to the quench. In all practical applications, enough care must be taken to limit the disturbance energy for such a tape to a value less than 12.8 J/m for stable operation. Following a quench, the superconductor is also required to be protected from overheating that ultimately leads to thermal stress. The avoidance of hot spots and thermal stresses following a quench can be effectively carried out by spreading the irrecoverable normal zone even more quickly over the entire cross section and length of the superconductors. In practice, such measures are feasible by triggering a heating tape co-wound with the HTS device with the onset of quench.

I-V characteristics of second generation 2G YBCO and BSCCO virgin high-Tc tapes at liquid nitrogen temperature of 77 K have been determined prior to their applications in various experimental applications. From I-V characteristic curve, the critical current \( I_c \) of a YBCO and BSCCO tapes were found to be 105 A and 148 A respectively in their self-field at 80 K. Based on these values, the strain induced degradation of the high temperature superconducting tapes have been studied in various practical geometries. In practice, in winding or in vacuum pressure impregnations, the tapes are bent as well as twisted. These stresses have not been adequately addressed in literature. Thus, the behaviors of HTS under such considerations were experimentally investigated in carefully designed experiments. Calibrated and graduated twisting induced strains were imparted onto the HTS and the degradations in the critical characteristics were measured as a function of strain as well as ramp rates of the transport currents. Results demonstrate that there is no substantial degradation in the normalized critical current \( \frac{I_c}{I_{co}} \). No degradation occurred corresponding to \( \theta/L \) between 0 to 16 (%/cm),
while there was a gradual $I_c/I_{co}$ degradation between 16 to 27 °/cm. A rapid degradation of $I_c/I_{co}$ occurred above 27 °/cm. After exposure the tape to such high stain, irreversible phenomena were observed in the tape, when untwisted. It was further observed that the normalized ‘$n/n_0$’-value for untwisted and straight conductor is 1.0. It remains constant up to twist angle per unit length of 16. Afterwards, it gets attenuated in a fashion such that it follows the same trend as that of $I_c$ degradation behavior. The degradations in such scenarios are attributed to the torsion induced damage in the microstructures of the superconducting tape. Till a threshold, the tape under the stress / strain carries the nominal transport current. As the shear strain increases the critical current sharply degraded.

Winding induced bending strain in a practical application has been experimentally studied using a prototype ‘D shaped’ magnet relevant to tokamak Toroidal Field Magnet system. The ‘D shape’ is a bending moment free configuration and BSCCO tapes have been used as the base high temperature superconductor in this winding pack. Double pancake configurations were adopted in this magnet winding pack. The wound tape showed a critical current of 93 A as against 148 A of the virgin tape. On this wound condition of the tape in the D shaped magnet, critical current behaviour under the different transport current ramp rates and under external magnetic fields has been experimentally investigated. The ramp rates have been experimentally found to be weakly affecting the critical characteristics in the range of 1.0 to 10.0 A/s. However, sudden drops of the coil voltage and hysteresis behaviour have been observed with the increase and decrease of ‘I’ the I-V curves in the D -shaped magnet. These are attributed to the hysteric behaviour of the matrix material sheath in the BSSCO tape. An induced normal zone propagation velocity has also been studied and is found to be in the expected range of 1-3 cm/s.

**Future works:**
Response of conduction cooled high temperature tapes and strands to spatial and temporal thermal disturbances have been investigated theoretically in this thesis. The temperature evolutions following an irreversible normal zone have been studied in depth in this thesis also. These studies are relevant to the possible applications of the tapes and
strands to a spectrum of applications ranging from utility to HVDC lines to motors and generators. The evolved criteria can as well serve as some design knobs to these possible applications involving high temperature superconductors. It is well known that the I-V characteristics of the high temperature superconductors vary with the intrinsic or applied strain. The critical characteristics also vary as a function of the ramp rate of the transport currents. These two critical aspects have been investigated both theoretically as well as through careful designed experiments in this thesis work. The theoretical results have been bench marked with experimental findings as well as with finite element modeling. In practical applications the wound high temperature superconductors always are subjected to such states in real operational scenarios. The extension of the high temperature superconductors to tokamak applications has been attempted with designing and fabricating a D-shaped prototype magnet and testing the magnet under different ramp rate conditions.

In future, the studies will be further extended keeping specific applications in mind. One of the works would involve in designing a twisted and/or breaded cable with high temperature superconductors. The configuration could be that of Rutherford type or that of cable-in-conduit-conductor type. The cabled tapes are expected to be degraded from their self-field induced electromagnetic forces (as a function of transport current), from uncompensated flux arising from terminations and joints in the magnet winding packs, from basic twisting of the conductor etc. These aspects would be explained in terms of degradation of the critical characteristics of the virgin tape as against the strains induced from the above considerations. The cabled HTS tapes have potential usage in many applications such as HVDC lines, in motors and in generators apart from in laboratory applications. Possible extensions could also towards tokamak or stellarator applications.

High Temperature based magnets are also now spoken for Heliotrons (Stellarator based reactors) and DEMO devices. A possible enlarged ‘D’ magnet is planned to be designed and fabricated. The stability of such a magnet in typical tokamak scenarios will be investigated experimentally. The stability and energy margin in bending moment free configurations will also be studies. It will further be investigated if such magnets could be
used as magnets with rapidly changing transport currents similar to central solenoids in a tokamak.

It has been reported in literature that the dry wound HTS tapes perform better than the potted or impregnated magnets. The impregnating insulation helps the winding pack to become a monolithic upon curing and thereby imparts additional stresses onto the winding pack. The D-shaped magnet experiment performed in this thesis work had employed dry winding of kapton insulations between the turns and the layers. The stresses on the windings had originated from the bending geometry only. Next, wet windings will be prepared on D-shaped magnets and the effect of cured insulations on windings will be experimentally investigated.

The 'normal zone propagation characteristics' in wound HTS tapes is another future aspects of investigation through experiments. The 'stability margin' or the 'energy margins' of the HTS tapes are intrinsically high. However, in wound geometrical configurations, initiations of 'quenched zones' are planned. Subsequent propagations of the normal zones are planned to be studied in experiments.

To sum up, we can say that the present work is an attempt to understand the High $T_c$ superconductors. Our work has been well recognized as evident from our published research papers in Journals of international repute. However, it would be interesting to extend the work because there is a lot to understand in this regards.