CHAPTER: V

CONCLUSION AND FUTURE WORK

5.1 Conclusion and Thesis Summary.................................................. V - 1

5.2 Future Work.................................................................................. V - 5
Bibliography..................................................................................... V - 8
Figures
5.1 Conclusion:

In this work, the stability, normal zone propagation characteristics, AC loss characteristics and the transport current ramp rate stability of multifilamentary superconducting strands with multiply connected stabilized regions is studied for the first time. Present day multifilamentary superconductors for Tokamak and Accelerator applications are mostly of this type. These strand cross sectional configurations are in sharp contrast to the earlier version of superconducting strands where the superconductor were largely distributed in the core and is surrounded by the stabilizer matrix. Consequently, most of the earlier theoretical and computational studies on superconducting strands have assumed either the superconducting region uniformly extending over the entire strand cross section or a superconducting core surrounded by matrix region. In this work, we have tried to adopt the exact strand configurations of the modern superconducting strands. In the analysis, the exact thermo-physical material properties of the strand constituents with field and temperature have been taken unlike the earlier simplistic analysis where they are assumed to be constant. Wherever applicable, experimental or technological inputs have been used in the analysis. The basic strand has been an actual strand which is used over 22000 km in the SST-1 Toroidal and Poloidal Field superconducting magnets. The strand parameters have been extensively experimentally investigated both from metallurgical and performance point of view [1-5]. In these senses, the work carried out in this thesis is not only new but also realistic and appropriate for future strand design.

Various necessary conditions for thermal stability, normal zone propagation and quench characteristics have been investigated in the framework of a newly proposed model. These results have been compared with those obtained from the conventional anisotropic continuum model based on averaged properties. It is demonstrated that the real temperature distribution in the strand cross section is more non-uniform than that which follows from the conventional anisotropic continuum model. This effect is attributed to the very spatial nature of the acting disturbances and on the distribution of the multifilamentary superconducting region and the stabilizer region inside the
composite strand. Fast transients either localized or distributed spatially are the most severe category of disturbances as far as the critical energies are concerned. In a Tokamak scenario for example, the plasma current disruption induced disturbances are fast transients type and acts most drastically on the Toroidal Field magnets. In the event of such disturbances, the critical quench energy is also dependent on the internal constitution of the composite strand and on the spatial location of the fast transients. It is demonstrated that the matrix plays a very important role in stabilizing the disturbances, and in general the disturbance located inside the multifilamentary region is more severe than if it is originated in the matrix region. The critical quench energy can also depend on the spatial location of the interfaces of the superconducting and stabilizing regions. In such cases, it is shown that the strands with higher filling coefficient or lower level void ratio are more stable to other cases as long as the physical properties of the stabilizer and superconductor remains constant. For a fixed critical current, the stability margin increases with decrease of the size of the superconducting region i.e. higher filling coefficient and increase of superconductor fraction in it. The temperature profile evolution is also shown to be critically dependent on the thermal properties and distribution of the matrix materials and multifilamentary regions inside the strand. This detail investigation has been published [6].

The AC loss characteristics of the multifilamenatry superconductors with multiply connected stabilized region has been attempted with a set of governing equations based on the filament and strand geometry. The ordering system in these analysis have been based on a long thin approximation where the geometry and excitation sources like transverse magnetic field vary slowly the axial co-ordinate of the strand. The twist pitch associated with the filaments inside the strand is considered to be large compared to the diameter of the strand and the diffusion time associated with the parallel conductivity has been considered comparable to the time scale of field variation. These result in a set of two coupled differential equations derived from Maxwell's equations with two unknowns: parallel electric field, the magnitude of which is parallel to the superconducting portion of the geometry and the transverse potential. The supplementary
The equation is the nonlinear constitutive relationship between the parallel component of the conductivity and the parallel electric field. An integrated loss expression for such strand and an integrated time constant has been found out taking the loss contributions from the stabilizers also. The conclusions are,

- The dominant loss is caused by the coupling loss. Thus, the assumption which is usually adopted that coupling loss being the dominant, other losses can be ignored to the first order estimation is justified to a large extent.

- The coupling loss becomes more with bigger and bigger copper core. The more the multifilamentary region is distributed closer to the center of the strand, the lesser become the coupling loss.

- The total loss (i.e. coupling loss and eddy current loss in the outer sheath and inner core together) becomes lesser as the multifilamentary superconducting region is distributed closer to the center of the strand. In such cases, the eddy current loss in the outer stabilizer sheath grows but much slower compared to the reduction of the coupling loss power density.

- As the multifilamentary superconducting region is distributed close to the center of the strand, the eddy losses in the outer sheath is no more negligible and it must be taken in to account while determining the time constant of the strand.

- The eddy current loss in the copper core is very small compared to both the coupling loss and the eddy loss in the outer sheath. For most of the estimation this can be neglected.

- The time constant of the strand with the eddy losses and without eddy losses will be almost the same.
• The effective time constant, $\tau_{\text{eff}}$ also grows similar to the growth of the coupling loss density.

• The reduction of the effective radius because of the dipole current is very small and the strand is quite insensitive to ramp fields as far as the interaction of this with the transport current is concerned.

An expression for the maximum current capacity of a strand has been found out as a function of the strand geometry, cooling conditions and the ramp rate of the current apart from experimental parameters derived from the measured V-I characteristics of the strand. Additionally, outer stabilizer sheath has proved out to have some influence of addition on to the maximum current carrying capacity of the strand. It seems that the more stabilizer distribution is on the outer sheath, the better it is for the maximum current carrying capacity. The degradation of the current carrying capacity reduces drastically when more and more stabilizer is distributed on the outer sheath compared to when the multifilamentary superconducting region is distributed throughout the strand cross section. The maximum current carrying capacity in transport current ramping scenarios is also a strong function of the cooling conditions, prevailing back ground field and temperature. Characteristics of various variants of the SST-1 strand have been investigated in this context including the variant-4, which is the final SST-1 strand configuration. This investigation includes the significant characteristics of the multifilamentary strands with multiply connected stabilized regions where such strands are employed in rapidly changing superconducting magnets. Nearest to such situations are the Tokamak Poloidal Field Magnets during the plasma start-up scenarios.

This thesis has attempted to characterize a modern technical superconducting strand completely from all respects. These are namely, from the view points of its thermal stability to disturbances and transients, its AC loss characteristics to time varying external fields and finally the maximum current carrying capacity of the strand when the transport current is ramped in it. In the course of this study, useful additional design knobs and criteria on such type strands have been derived and highlighted with respect to their
suitability for tailor made applications like in Tokamak magnets. However, manufacturing of such strands in an industrial scale must be feasible from technological and metallurgical considerations.

5.2 Future work:

So far, we have carried out various analysis of the state-of-art low temperature technical superconductor assuming that it is cylindrical in shape and it has a circular cross section. The variation along the z-axis has been neglected in investigating the thermal stability with respect to the fast transients as well as in the investigation of the maximum current carrying capacity of the strand in the ramp rate scenarios. This was enough since in most practical cases, the geometry allows such an assumption. As a future work, a mathematical model can be developed to investigate the thermal stability conditions and quench propagation characteristics of technical modern superconductors in two dimensional cases (fig 1). As shown in the figure, the two dimensions concerned here would be the radial (r) and axial (z) co-ordinate in case of a multifilamentary strand with cylindrical cross section. The disturbances concerned would be an extension of the type of the disturbances considered in chapter-2. Unlike the disturbances localized in marginal interfaces of the stabilizer-superconductor interfaces, these 2-D disturbances would be spread over a finite axial extent. The heat propagation can be described as follows:

\[ C_i \frac{\partial T_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_i r \frac{\partial T_i}{\partial r} \right) + \lambda_i \frac{\partial^2 T_i}{\partial z^2} + q(r_i, z_i, t) + \begin{cases} 0, & T_2 < T_{cs} \\ G_i, & T_2 \geq T_{cs} \end{cases} \]

with the following boundary conditions on \( r \)

\[ T_1 = T_2, \lambda_1 \frac{\partial T_1}{\partial r} = \lambda_2 \frac{\partial T_2}{\partial r} \text{ at } r = r_1 \]

\[ T_2 = T_3, \lambda_2 \frac{\partial T_2}{\partial r} = \lambda_3 \frac{\partial T_3}{\partial r} \text{ at } r = r_2 \]

\[ \lambda_3 \frac{\partial T_3}{\partial r} + h(T_3 - T_0) = 0 \text{ at } r = r_3 \]
and the temperature as well as its derivative is continuous along the z direction. The initial condition is that before the onset of any kind of disturbances, there exists no temperature gradient in any of the region of the strand cross section i.e either in 'r' direction or in 'z' direction. It can be represented as

\[ T_i(r,z,0) = T_0 \]

In these analyses, the disturbances will be finite in radial width as well as of final extent in axial direction. Physically, they will be annular solenoid type of disturbances bounded by \( r_1 < r < r_1 + \delta r \) in radial width and of axial length \( 2\delta z \) around \( z = 0 \) in any of the three regions i.e. matrix core or multifilamentary superconducting region or in the outer sheath region. The choice of \( \delta r \) will be around one filament diameter where as the axial length of this disturbance source could be small or large.

Thus, a full range of thermal stability conditions and normal zone characteristics could be obtained considering both the transverse and longitudinal dynamics. However, these investigations are likely to be numerically cumbersome and difficult. It may require advanced computing facilities and large memory storage spaces. The convergence criteria, which we had adopted in the 1-D case, might be quite difficult to obtain. Presently, we do not have adequate facilities to carry out these investigations. However, it is hoped that after comparing the results obtained from such a cumbersome investigations with those what we have obtained in this thesis work, not much simplification on the practical usage may happen. Results as they have been obtained from the 1-D model would be more than sufficient. Nevertheless, such a study may be pursued from academic point of view. At this stage, numerical experiments may be needed for stability of superconducting state of real conductor with Cu and CuNi matrix comprising of such strands other than what we have considered in case of SST-1 strand. Resistance barriers like CuNi etc around each of the superconducting filaments or around the strand as used in some of the present day highly AC magnets have not been
considered in this thesis work. In fact, superconductors used in Superconducting Magnetic Energy Storage (SMES) devices or in AC electrical machines like Superconducting Generators use high resistance barriers both around the filaments and around the strands. We do not have complete technical data on such strands either to extend our analyses to those cases. Further, since our focus was on multifilamentary superconducting strands primarily used for Tokamak and Accelerator magnets, we have not considered such options. However, such analysis may be very relevant to superconductors used in electrical industries and electrical machines.

Similarly, the AC loss formalisms as developed in chapter - 3 can also be extended to superconductors mentioned above. There will be changes in the boundary conditions in the superconductor-matrix interfaces as a result of the high resistance materials. This in turn will make the numerical computations more difficult and even more time consuming and the probability of not attaining the converged correct solution would be more. However, some smart numerical algorithm and faster machines may be able to overcome these computational difficulties. This can be a detailed future work.

The 1-D formulation in investigating the 'maximum current' carrying capacity of the strand may also be modified and expanded to predict the ramp rate characteristics real cable-in-conduit-conductor or in a wound magnet. In the case of a CICC, the inter-strand contacts induced phenomenon will be required to be modeled and the twisting algorithm will have to be somehow incorporated. In case of a wound magnet, the problem will be even still more complex.