STABILITY OF SUPERCONDUCTING MULTIFILAMENTARY STRAND WITH MULTIPLY CONNECTED STABILIZING REGIONS

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2.1 Introduction

Stability of multifilamentary superconducting strand to various kinds of disturbances is the most critical aspect of its suitability to superconducting magnet systems. The disturbances that acts on superconductors in most of the practical situations have their origins from time varying fields or currents. These disturbances have both spatial and temporal characteristics. They can be localized point disturbances in space or could be extended disturbances over considerable length of the superconductor. Similarly, they can have extended single shot or multi shot duration or can be fast transient [1]. In typical Tokamak and accelerator operational scenarios, the superconductors are usually subjected to the worst kind of disturbances. The fast transient disturbances are considered to be the most dangerous to superconducting magnet systems [1,3]. One appropriate example is the fast plasma current disruption induced disturbance acting on the superconductors of the Toroidal Magnets in a superconducting Tokamak. The thermal stability of superconductors in such situations have been usually described by the heat conduction equations, where the temperature evolution in the composite superconductor as a result of external or internal disturbances are analyzed by the anisotropic continuum model. The present day technologically advanced multifilamentary superconductors, as stated in the earlier chapter, have usually a stabilizing core, annular multifilamentary region with diffusion barriers in between the filaments and an outer stabilizing sheath for operations in demanding situations like that in Tokamaks and Accelerators. Thus, the existing theory can not simply be extended to the presently adopted multifilamentary superconducting strands. The detailed thermal stability criteria and conditions of such strands in response to fast transients have been investigated theoretically and numerically in this chapter. A new model has been proposed for this study. The thermal stability characteristics for such superconducting strands have been parametrically investigated when such disturbances originate at different locations and regions in the strand cross section. The thermal stability as a function of the cooling conditions and fraction of the superconductor in the strand cross section are also being studied. Instead of assuming temperature and field independent properties for theoretical simplicity as were done in
most of the earlier studies, appropriate temperature and field dependence of the strand properties have been taken wherever it is applicable.

2.2 Model:

Consider an infinitely long cylindrical superconducting strand having multiply connected stabilizing regions as shown in fig 2.1. The inner stabilizing core is extended up to a radius \( r_1 \), the annular multifilamentary region extends up to a radius \( r_2 \) having superconducting filaments in a stabilizing matrix, and an outer stabilizer sheath around the multifilamentary region extends up to the radius of the strand, \( r_s \). The outer surface of the strand is in direct contact with the coolant, which is helium. The strand carries a steady current \( I \) which is uniformly distributed over the multifilamentary superconducting area. The situation of gradual transport current penetration from outside to inside of the multifilamentary region is not considered here. Such phenomenon is associated usually with a current ramp. A steady transport current situation has been considered established all over the multifilamentary cross section region. The stability aspects arising from the current ramp up cases have been investigated in chapter 4 of this thesis. In this model, the strand is further uniformly cooled to the coolant temperature \( T_0 \) along its perimeter with a heat transfer co-efficient \( 'h' \). This also implies that, before the onset of any kind of disturbances, there exists no temperature gradient in any of the region of the strand cross section. Assuming axial symmetry, the heat propagation in such a strand with respect to infinitely long transient thermal disturbance, which is deposited instantaneously inside the strand within a region that extends from radius \( r_1 \) up to a radius \( r_1 + \delta r \) can be written by an one dimensional equation \((i = 1,2,3)\)

\[
C_i \frac{\partial T_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_i r \frac{\partial T_i}{\partial r} \right) + q(r_i, t) + \begin{cases} 0, & T_2 < T_0 \\ G_i, & T_2 = T_0 \end{cases} \quad (2.1)
\]

The boundary conditions being satisfied at all the times are given by,
and, the initial condition as explained above has the form,

\[
T_1 (r,0) = T_0
\]  

(2.3)

In these equations, \( C_i \) and \( \lambda_i \) are the heat and thermal conductivity coefficients respectively. \( T_{cs} = T_{cs} - (T_{cs} - T_0) \frac{1}{I_c} \) is the current sharing temperature in the superconductor composite area with critical current \( I_c \) and critical temperature \( T_{cb} \) in a given stationary background field \( B \). The local heating pulse power is denoted as \( 'q' \) and the joule heat generation in the strand is given as \( 'G_i' \).

The joule heat release \( 'G_i' \) in all three regions of the superconducting strand is calculated as follows. If the superconducting cross section has a temperature less than \( 'T_{cs}' \), then no heat generation takes place. If \( T_2 > T_{cs} \), then certain fraction of the transport current is transferred to the matrix. Consequently, an additional electrical voltage appears in the strand, and joule heating occurs both in the pure stabilizing region as well as in the annular multifilamentary superconducting area. Taking into consideration the appearance of the normal zone in the superconducting region, the heat that is generated within, is defined in accordance with the dynamics of the normal zone propagation. Heat generation takes place in the matrix region completely due to the total transport current as long as the temperature in the multifilamentary superconducting region, \( T_2 > T_{cb} \). Thus, the value of \( G_i \) is written as,
Here, $J_m$ and $J_2$ are the current densities in the matrix and in the multifilamentary superconducting region respectively. $E = J_m \rho_m$ is the electric field into the strand with $\rho_m$ being the matrix specific resistivity. These values critically depend on the conditions associated, with the origin and on the propagation characteristics of the normal zone inside the superconducting region of the strand. Alternately, the kinetics of the normal zone in the radial direction of the round cylindrical strand depends on the location of the initial disturbance heat pulse. Therefore, the current redistribution inside the strand is also influenced by both the spatial and temporal characteristics of the source of the disturbance.

Let us write equations describing the currents inside the different regions of such a multifilamentary superconducting strand with multiply connected stabilizing regions in response to a disturbance impulse. Suppose that, the heat release occurs in the local domain of the strand adjoining the marginal surface of $r = r_i$ on the part of its superconducting region $r = r_i$ (fig 2.1). In this case the normal zone appears on the internal radius of the region containing the superconductor. So, an equation of current balance inside the strand takes the form,

$$I = I_m + I_s + I_n$$

Here, $I$ is the transport current, $I_m$ is the current flowing through the matrix, $I_s$ is the current in the region of composite superconductor in which temperature has not yet reached $T_{CS}$ and $I_n$ is the current in the part of the composite which has normal zone. This is justified by the fact that the characteristic normal zone spread over the multifilamentary superconductor region depends on the transverse quench propagation velocity and the thickness of the zone where quench heat generation occurs. The thickness of the heated zone evolves until the whole region becomes normal. This thickness, on the other hand, is adiabatically controlled by the thermal diffusion processes which, in turn is a function of
the thermal conductivity and heat capacity of the superconductor and matrix material. The respective values are equal to,

\[ I_m = J_m A_m \]
\[ I_s = \frac{1}{\eta_2 A_2} \Sigma_A \]
\[ I_n = \int J_c(T) dA \]

Here, \( A_m = \pi r_1^2 + \pi \left( r_2^2 - r_1^2 \right) \left( 1 - \eta_2 \right) + \pi \left( r_3^2 - r_2^2 \right) \) is the area of the conducting matrix in the strand cross section. \( \eta_2 \) is the volume fraction of the superconductor (often called 'filling coefficient') in the superconducting composite region having cross section \( A_2 = \pi \left( r_2^2 - r_1^2 \right) \). \( \Sigma_A = \left( r_2^2 - r_n^2 \right) \eta_1 \) is the area in the transverse cross section of the composite region which is still in the superconducting state. \( r_n \) is the radial co-ordinate of normal zone defined from equation \( T(r_n, t) = T_{cs} \). \( \Sigma_n \) is the area in the transverse cross section of the composite region being in normal state \( \left( \Sigma_s + \Sigma_n = \eta_2 A_2 \right) \)

Using these formulae, after little bit of algebraic manipulation, the current density in the matrix can be found out as,

\[ J_m = \frac{I \left( 1 - \frac{r_n^2}{r_2^2} \right) - \int J_c(T) dA}{A_m} \]

while the current densities in the part of the composite superconducting multifilamentary region is given as,

\[ J_2 = \begin{cases} 
\eta_2 J_c(T) + \left( 1 - \eta_2 \right) J_m, & r_1 \leq r \leq r_n(t) \\
\frac{I}{A_2} + \left( 1 - \eta_2 \right) J_m, & r_n(t) \leq r \leq r_2 
\end{cases} \]
In similar manner, the instant values of currents at the action of disturbances resulting in the appearance of the normal zone on the outer radius of the superconducting composite region could also be written. The current density, in such situations, in the matrix is given as,

\[
J_m = \frac{I\left(1 - \frac{r_1^2}{r_2^2} + \frac{r_2^2 - r_1^2}{r_2^2 - r_1^2}\right) - \int J_c(T) dA}{A_m}
\]

and, the current density in the region filled by the superconductor in the strand cross section is given as,

\[
J_2 = \begin{cases} 
\frac{I}{A_2} + (1 - \eta_2) J_m, & r_1 \leq r \leq r_a(t) \\
\eta_2 J_c(T) + (1 - \eta_2) J_m, & r_a(t) \leq r \leq r_2 
\end{cases}
\]

With these descriptions of the model, we proceed to calculate the physical quantities associated with the superconducting material and the matrix material. As indicated in chapter-I of this thesis, we will confine our attention to the most widely used and studied technological superconductor NbTi. The matrix material chosen for the calculation is also most commonly employed stabilizer material i.e. copper. Appropriate temperature and field dependent physical properties of these materials have been taken in the numerical simulation.

The superconductor critical temperature as a function of the magnetic field has been taken in the form

\[
T_{cb} = T_{c0}\left(1 - \frac{B}{B_{c0}}\right)^{0.5}
\]
The critical current has been estimated in compliance with simple model dependence of

\[ I_c = \frac{\alpha I_{C2} A_2}{B} \left( 1 - \frac{T_0}{T_{CB}} \right) \]

where, \( T_{CB} \), \( B_{CB} \) and \( \alpha \) are the known intrinsic parameters of the superconductor. Constant '\( \alpha \)' makes it possible to approximate with adequate accuracy the experimental dependence of NbTi superconductor with experimentally measured critical current. In case of SST-1 strand the value of \( \alpha \) is \( 3.803 \times 10^6 \text{ AT/cm}^2 \).

The heat capacity of the NbTi superconductor has been calculated using the data [2] and those supplied by the SST-1 strand manufacturer, M/s Hitachi Cable, Ltd.

\begin{align*}
C_{\text{NbTi}} \left[ \frac{J}{\text{cm}^3 \text{ K}} \right] &= \begin{cases} 0.812 \times 10^{-3} T \frac{B}{B_{C0}} + 4.273 \times 10^{-5} T^3, & T \leq T_{CB} \\ 0.812 \times 10^{-3} T + 1.29 \times 10^{-5} T^3, & T > T_{CB} \end{cases}
\end{align*}

The heat capacity of the copper matrix has been estimated in accordance with [3],

\[ C_1 = C_3 = C_m = 8 \times 10^{-6} T^3 \left[ \frac{J}{\text{cm}^3 \text{ K}} \right] \]

The heat capacity of the superconducting multifilamentary composite region is defined as,

\[ C_2 = C_s \eta_2 + C_m (1 - \eta_2) \]
The heat conductance of stabilizer material copper is calculated in compliance with Wiedemann-Franz law,

\[ \lambda_1 = \lambda_3 = \lambda_m = 2.45 \times 10^{-8} \frac{T}{\rho_m} \left[ \frac{W}{\Omega \cdot K} \right] \]

and, for the heat conductance of superconducting composite section, the contribution of the matrix only is being taken into account

\[ \lambda_2 = \frac{1 - \eta_2}{1 + \eta_2} \lambda_m \]

The magnetic field dependence of the electrical resistivity of the copper is given by [4],

\[ \rho_m = (2.13 + 0.605 B) \times 10^{-8} \left[ \Omega \cdot cm \right] \]

The finite difference method has been used in solving the problem described by the system of equation (2.1)-(2.3). The calculations have been carried out for a technical superconducting composite strand of 0.86 mm in diameter placed in a steady background field of 5 T. The NbTi superconductor properties have been taken as per the experimental parameters of the SST-1 strand. They are as follows, \( T_{co} = 9.5 \) K, \( B_{co} = 14 \) T, penning constant \( \alpha = 3.803 \times 10^6 \) AT/cm², local filling ratio in the multifilamentary region \( \eta_2 = 0.64 \).

The above numerical analysis is extended to predict the thermal stability, quench and current sharing characteristics of a real strand having multiply connected stabilizing regions. This strand is the SST-1 strand, which has been manufactured in an industrial scale [5-6]. These strands have been manufactured over lengths of 22000 Kms. This strand has been adopted as the base strand for the Cable-in-Conduit-Conductors (CICC) of the
Steady State Superconducting Tokamak (SST-1). CICC made from such strands have been used in the superconducting Toroidal and Poloidal Field Magnet system. The SST-1 strand parameters used in this numerical experiments and, from which the strand behavior is predicted are \( r_1 = 245 \) micron, \( r_2 = 330 \) micron and \( r_3 = 430 \) micron. The operating current has been taken as 75 Amp in 5 T background field (experimentally obtained critical current of 262 A in identical conditions with 0.1 \( \mu \)V/cm criteria). This value of the operating current roughly corresponds to the operating currents of the strands in the SST-1 Toroidal Field magnets.

In these numerical investigation the heat pulse has been assumed to be a step function of the form

\[
q = \begin{cases} 
\text{Const}, & t \leq \tau \\
0, & t > \tau 
\end{cases}
\]

The duration over which the disturbance pulse is applied is transient in nature (\( \tau = 10 \)\( \mu \)s).

This duration is similar to the envisaged plasma current disruption induced disturbances in SST-1. The pulse application is also localized in nature over a radial width of \( \delta r \) and is on a small cross section of the multifilamentary region. In the numerical estimations \( \delta r = 10 \) micron. The choice of 10 micron is motivated from the fact that in most of the modern superconducting strands the filament size is of the order of 10 micron or less. The nominal filament diameter in SST-1 strand is also 10 micron. With the choice of an annulus of 10 micron inside the multifilamentary region, it is assumed that one layer of the filament has gone normal. Alternately, this corresponds to a situation when the disturbance energy is selectively deposited on one layer of filaments only. Theoretically, such heat pulse asymptotically approaches the values of the of the critical energy corresponding to instantaneous heating by infinitely long disturbances in small region of the strand cross section.
The procedure for finding the 'critical disturbance' is based on the determination of the final thermal state of the strand after the applied disturbance ceases. Thus, the maximum value of the permissible disturbance is determined. For a given accuracy of the critical energy determination 'ε', the superconducting properties of the strand are fully recovered if \( q < q_{\text{crit}}^{(e)} \). In the simulation this accuracy is of the order of \( 10^{-5} \). In the violation of the above condition, the irreversible transition of the strand into the normal state occurs for all \( q > q_{\text{crit}}^{(e)} \). Thus the critical energy computed is equal to,

\[
E_q = q_{\text{crit}}^{(e)} \tau A_i
\]

where, \( A_i = \pi \left[ (r_i + \delta r)^2 - r_i^2 \right] \) is the area in the cross section where the disturbance takes place.

2.3 Verification of the Model described by equations (2.1)-(2.3):

We compare the results of stability calculations that can be obtained within the framework of different models. Consider a composite with the superconductor being uniformly distributed over the cross section. This has been the case in most of the models. The upper limit of the permissible disturbance energy in such a situation shall be calculated from the model described by equation (2.1) – (2.3). The results obtained from these calculations will be compared with those critical energies obtained using the generally accepted model of superconducting composite formulated within the framework of the anisotropic continuum model [1,3,7-9] with effective heat and electro-physical parameters based on current sharing. The anisotropic continuum model can be stated with the following initial boundary equations
The specific heat capacity, $C$ and the coefficient of heat conduction, $\lambda$ of the composite are given as follows,

$$C = C_s \eta + C_m (1 - \eta)$$

$$\lambda = \lambda_m \frac{1 - \eta}{1 + \eta}$$

where, for the strand under consideration, the filling coefficient is equal to $\eta = 0.1322$. (In the strand concerned, the superconductor is distributed in the annular multifilamentary region having a filling coefficient of 0.64. However, if this superconductor is distributed over the total cross section of the strand, the effective filling coefficient turns out to be 0.1322.)

The rectangular disturbance impulses localized at $r = r_i$ (disturbance 1: $r_i = 2.45 \times 10^{-2}$ cm, $\delta r = 10^{-3}$ cm, $\tau = 10 \mu s$) and at $r = r_3$ (disturbance 3: $r_i = 4.2 \times 10^{-2}$ cm, $\delta r = 10^{-3}$ cm, $\tau = 10 \mu s$) are considered as the external heat sources. Critical energies as functions of the current which have been calculated for uncooled strand have been plotted in fig 2.2. The solid line corresponds to the calculations carried out in accordance with equation 2.4. For fast transient disturbances, the strand in all practical purposes is practically uncooled, since the helium in contact gets instantaneously evaporated. Thus, the assumption of uncooled strand is justified here. Markers show the critical energies determined in accordance with the model described as per equation 2.1 to 2.3. The shown results clearly demonstrate excellent agreement of the model formulated by equation 2.1-2.3 with those predicted by anisotropic continuum model described by equation 2.4.
2.4 Thermal Stability Conditions: Results and Discussion

The critical energies for fast extended disturbance ($\delta r = 10^{-3}$ cm, $\tau = 10$ $\mu$s) localized in various parts of the uncooled strand cross section are shown in fig 2.3. Calculations have been carried out within the framework of model described by equation 2.1-2.3 and 2.4. Four possible different types of heat sources with respect to the location inside the strand cross section have been investigated. They are,

- Disturbance 1: $r_1 = 2.45 \times 10^{-2}$ cm
- Disturbance 2: $r_2 = 3.20 \times 10^{-2}$ cm
- Disturbance 3: $r_3 = 3.30 \times 10^{-2}$ cm
- Disturbance 4: $r_4 = 4.20 \times 10^{-2}$ cm

The insert on fig 2.3 shows the dependence of the critical energy $E$ in J/m on the pulse duration. This has been calculated for disturbances of type 3 at a transport current of 75 A. From this figure, it is evident that for a duration $\tau < 10^{-2}$ s, the disturbance duration does not, in practice, influence the critical energy. The results given in fig 2.3 make it possible to formulate the physical characteristics of the stability of such superconducting strands with respect to the disturbances.

Thermal stability conditions depend strongly on the location of the disturbance heating pulse. If the heat release takes place directly into the superconducting region, the corresponding critical energy is less than the energy necessary for transition into normal state as compared to when the disturbance is localized in the non-superconducting matrix. This feature is explained below in the following paragraphs.

From the well known thermal stability theory of the superconductor, the characteristic permissible length of the normal zone initiated local pulse is called the MPZ-domain. The MPZ critically influences the heat diffusion mechanisms in the propagation of the disturbance pulse within the superconducting composite both in transverse and
longitudinal direction, which consequently affects the stability of the superconducting state [1]. For action extended heat impulse, the transverse size MPZ domain is equal to the maximum length of the normal zone on which it can spread in the transverse cross section with the condition of its superconductivity conservation [10,11]. These regularities are found to be characteristics for superconducting compound. As an illustration, the possible state curves describing the kinetics of normal zone in the transverse cross section of uncooled strand as well as the time evolution of the current and temperature profile at the interface \( r = r_2 \) are shown on fig 2.4 and 2.5. The disturbances are of the type 23, 32 and 3 with energy close to the critical energy. It has been demonstrated that for given type of disturbances, the characteristics of the superconducting domain heated by critical heat impulse and kinetics of normal zone practically do not change the local heating characteristics within the various regions of the strand. The magnitude of the critical disturbances in different regions do differ but the heating characteristics remains the same in both the new model (equation 2.1-2.3) and the anisotropic continuum model (equation 2.4)

The influence of the heating of the non-superconducting components present in the multifilamentary region of the composite strand on the process of redistribution of heat in its superconducting part has been investigated next. In the case of disturbance impulses of type 1 and 23, the thermal source directly heats up the superconducting layers of the composite strand. As per the model described by equations (2.1)-(2.3) at \( h = 0 \), the average temperature increase in this region may be written as

\[
\int_{r_1}^{r_2} C_2(T) \frac{\partial T_2}{\partial t} \, rdr = r_2 \lambda_2 \left. \frac{\partial T_2}{\partial r} \right|_{r=r_2} - r_1 \lambda_2 \left. \frac{\partial T_2}{\partial r} \right|_{r=r_1} + \int q(r, t) \, rdr
\]  

(2.5)

The above inequality indicates that the temperature profile evolution in the superconducting region definitely influences the heating and heat propagation in the adjacent matrix region. However, at the action if such kind of disturbances the stability condition turns out to be identical to those of composite superconductor heat stabilization.
that follows from the anisotropic continuum model with averaged heat and electro-physical parameters. In other words, from the heat stabilization theory, at the actions of disturbances localized in the superconducting region of the wire, the compound behaves as if the conductor is evenly distributed with a given amount of superconductor over the whole cross section.

On the contrary, for the disturbances of type 32 and 3, from the heat conduction equation, it follows that at $h = 0$ the average increase of temperature of the superconducting region is described by the inequality

$$
\int_{r_1}^{r_2} C_2(T) \frac{\partial T_2}{\partial t} r dr = \int q(r, t) r dr - \int_{r_1}^{r_2} \int C_3(T) \frac{\partial T_3}{\partial t} r dr - r_1 \lambda \frac{\partial T}{\partial r} \bigg|_{r=r_1} 
$$

(2.6)

It is evident that part of the heat from the source is necessarily accommodated by the hat capacity of the matrix. That is the reason as to why in such cases, the stability conditions will be defined not only by the gross amount of heat release but also by the matric physical properties, matrix distribution over the strand cross section and the location of the interfaces. Therefore, variation in the thermal stability conditions is expected with the variation of the above parameters.

Supporting such thermal behavior, fig 2.6-2.8 demonstrate the temperature and normal zone evolution in uncooled superconducting compound ($h = 0$) for a transport current $I = 100$ A. Here, the disturbance impulse are up to the critical energy $E = 0.1321 \times 10^{-2}$ J/cm. Corresponding results based on anisotropic continuum model described by equation 2.4 has also been presented for comparison.

The temperature distribution along the strand radius at time $t = 5 \times 10^{-7}$ s in response to various types of disturbances as described earlier, has been shown in fig 2.6 on the strand cross section. At this instant, the normal zone does not exist but the disturbance heat pulse is on. The time evolution of the strand temperature in sections where normal
zone appears and its kinetics at the action of the considered disturbances are depicted in fig 2.7 and 2.8 respectively. The temperature evolution of the superconductor-matrix interfaces under the action of the above disturbances are depicted in fig 2.7 as per the new model as well as the anisotropic continuum model, where as the normal zone propagation under these disturbances up to critical disturbances are shown in fig 2.8. These results demonstrate the following. As a result of the variation of the disturbance source location within the strand cross section, the temperature of surfaces where normal zone is initiated, changes noticeably if and only if the variation of the spatial localization of disturbance impulse is accompanied by the change in the strand physical properties. The variation of the strand temperature profile does not bring essential changes in the temperature of the superconducting region and in the condition of the normal zone initiation. At the same time, it may be noted that at the action of the disturbances situated in the superconducting region, the increasing in temperature occurs more intensely than at the action of disturbances localized in the matrix. As discussed earlier, this is related to the stabilizing nature of the matrix.

Changing the spatial coordinates of the superconducting region and stabilizer interfaces can also influence thermal stability conditions. Critical energies depending on the fractional cross section occupied by the superconductor and its location inside the strand are shown in fig 2.9 and 2.10 for a transport current of 75 A and for disturbances of type 1 and type 3. In the first case the filling coefficient of superconducting region is kept constant ($\eta_2 = 0.64$) and the coordinates of the interfaces $r = r_1$ and $r = r_2$ are varied with the constraint $I_C = const.$ In the second case, it is considered that $r_1 = 0$ but the filling factor and $r_2$ are changed in accordance with the fixed $I_C$ of the composite strand. The later case corresponds to a wide version of recent technical superconductors in which the multifilamentary superconducting region is being surrounded by a stabilizer sheath only.

As expected, in response to the disturbance pulse localized in the superconducting region, the internal geometric distribution of the composite practically does not influence the stability of the superconducting state. In this case, it behaves as if it follows from the anisotropic continuum model with averaged physical parameters. On the other hand when
the disturbance impulse is localized in the non-superconducting matrix, the condition of transition of superconducting to normal state is dependent on the distribution of components inside the strand. The most noticeable change in the critical energy takes place when the filling coefficient in the strand cross section is altered. Fig 2.11 and 2.12 describe the temperature rise of the strand in the event of a disturbance of type 3 for a fixed filling coefficient where the critical energy, \( q = 5 \times 10^5 \text{ J cm}^3 \) and with the change in the filling coefficient the critical energy, \( q = 15 \times 10^5 \text{ J cm}^3 \). For both the cases, the transport current is kept at 75 A. For a fixed filling coefficient of 0.64 and for different superconductor-matrix interface locations, the temperature evolution of the composite strand is shown in fig 2.11 whereas the filling coefficient is varied in fig 2.1. Illustrated results demonstrate that the thermal state of the superconducting region depends not only on the matrix heat capacity for given disturbances. As mentioned in equation 2.5 and 2.6, the time gradient of the temperature is an influencing factor also. Therefore, with variation of superconductor region inside the strand, different heating phenomena of the superconductor can principally exist. The change of heat flow in the superconducting region from the matrix which is equal to

\[
\lambda_2 \frac{\partial T_2}{\partial r} \bigg|_{r=r_s} = \frac{qA_1}{\pi r_s^2} - \frac{1}{r_s^2} \int_{r_s}^{R_s} C_3(T) \frac{\partial T_3}{\partial t} r dr
\]

This does not cause substantial change of superconductor temperature as long as the filling coefficient is constant (fig 2.11). On the contrary, when the filling coefficient is allowed to vary with the constraint that \( I_C = \text{const} \), there can be an appreciable increase in temperature (fig 2.12). However, as shown in fig 2.11 and 2.12, the change of surface temperature is opposite to that of the superconductor-matrix interface behavior.

Additional numerical experiments have been carried out to determine the changes in the stability conditions attributed especially to varying the filling coefficient. The following assumptions have been made in these detailed investigations,
Case 1: heat capacity and the coefficient of heat conduction are not dependent on the filling coefficient and are described in similar manner to that of the matrix.

Case 2: heat capacity depends on the filling coefficient as formulated in the initial model but there is no change of the heat conduction coefficient of the annular multifilamentary region which is assumed to be equal to that of the matrix.

Case 3: the coefficient of the heat conduction of the heat conduction of the superconducting region depends on \( \eta_2 \) but its heat capacity is equal to the matrix heat capacity.

Results of the corresponding calculations are presented in fig 2.10. It is seen that under the discussed case, increasing the stability margin is related to the changing of the heat conduction coefficient of the superconducting section, which decreases with increasing of the filling coefficient.

Significant change in the stability of the multifilamentary strand is related to the thermal properties of its components as well as on the current redistribution phenomena between the superconductor and the adjoining matrix. There are direct connections between the temperature change and the current redistribution. To support the above claims, fig 2.13 and 2.14 show the current sharing between the superconducting region and the stabilizing regions (inner copper core and outer copper sheath). For two types of disturbances (fig 2.13) and for two types of strand (fig 2.14) at transport current \( I = 100 \, \text{A} \) and \( \eta_2 = 0.64 \). It is seen that in response to the normal zone growth in the strand, the transport current is being quickly shared between the multifilamentary superconducting region and two stabilizing regions. In these particular examples, the current sharing occurs at about \( 2 \times 10^{-5} \, \text{s} \) in response to critical thermal disturbance with a duration of \( 10^{-5} \, \text{s} \). Current sharing occurs even before the termination of the imposed disturbance. During this current sharing process, the current shared in the outer sheath is more than that of the inner core as the inner core resistance is more than that of the outer sheath. At the initial stage, it
is also observed that there exists an inhomogeneous current distribution, which affects the temperature distribution along the cross section of the sheath. It is also essentially inhomogeneous (fig 2.6 and 2.15). Its maximum value is reached in the region where the heat source is located. As quench occurs, the current shared by the inner core and outer sheath is proportional to their respective resistances. The temperature profile even in the short time scale becomes uniform after quench. This can be seen in fig 2.15.

It is interesting to study the existence of inhomogeneous temperature profile in the strand cross section. Usually in the theory of heat stabilization, it is assumed that the appearance and propagation of the normal zone occur over a strand cross section, which has a uniformly distributed temperature. Results outlined in fig 2.5 and 2.15 demonstrate the inaccuracy of this assumption. In this context, it is worth investigating the comparison of the results obtained from the modeling the conductor with heterogeneous physical properties first based on the model described by equations 2.1-2.3 and then based on the anisotropic continuum model described by equation 2.4. In fig 2.15 and 2.16 for the disturbances of type 3, I = 100 A and h = 0, solid lines show the temperature dependencies calculated based on model described by equation 2.1-2.3 and the dotted lines correspond to the results obtained from the anisotropic continuum model described by equation 2.4. Curves on fig 2.15 correspond to various cases up to the critical disturbance. In fig 2.16, the strand temperatures in the event of disturbances close to the critical disturbance are presented. Markers show the change of interface temperature, where the normal zone is initiated. The shown dependencies demonstrate the importance of taking in to account the heterogeneity of the components in the composite strand as far as their physical properties are concerned, on the results of its calculation of its temperature profile. It is evident that, to model the composite strand using the average physical properties of the strand cross section, as is usually done, is clearly not always enough. This is apparent both in the initial stage of heat diffusion and after quench. Additionally, computation shows a difference in the computing of the temperature profile based on our model described by equations 2.1-2.3 and that described by equation 2.4. This difference decreases for disturbances localized in the superconducting part of the strand.
Another important aspect of thermal stability is undoubtedly the effect of cooling conditions. So far, since the disturbances are fast transients, the uncooled \( (h = 0) \) assumptions is justified. However, in this section we will investigate the effect of high heat transfer coefficient on stability conditions. Other motivation of carrying out this study is from the fact that in case of fast transient disturbances in superconducting magnets, acceleration of helium flow occurs, which is known to increase the heat transfer coefficient few fold momentarily. For this purpose a high heat transfer coefficient of 0.2 W cm\(^{-2}\) K\(^{-1}\) is being chosen to compare the thermal stability with that obtained from uncooled cases based on model described by equation 2.1-2.3. Fig 2.17 shows the critical energy as a function of transport current under disturbance of type 1 and 3. It has been seen that in case of the action of infinitely long disturbances the influence of the heat transfer coefficient on stability conditions is small within the current range exceeding the so called 'steady state stabilization current'. For SST-1 strand, this value is 58 A at 5 T. In the base of the given effect, also lies possible non-uniform temperature distribution along the strand cross section. It follows from [12] that, in similar events a more general form of steady state stability condition for a composite superconductor has the form

\[
J^2 \int_{A} p(T) \, dA \leq \int_{P} h(T - T_0) \, dP
\]

Here, \( J \) is the current density associated with the transport current, \( A \) is the cross sectional area of the composite and \( p \) is the cooled perimeter.

The above condition shows the primary physical characteristics of the processes responsible for the restoration of the superconductivity of the conductor. The steady state stabilization depends on the surface temperature as well as on the temperature distribution along the strand cross section. These aspects play an important role in stability conditions. Clearly, the surface temperature decreases with increasing heat transfer coefficient. Thus, the critical energy in the real case is always less than the corresponding value calculated under the assumption that the strand cross section has uniform temperature.
2.5 Conclusion and Summary:

A new model for multifilamentary superconductors with multiply connected stabilizing regions have been made where the thermal stability conditions in response to fast transients like that of plasma disruption induced disturbances in a Tokamak, have been discussed in detail. In the numerical simulations, the properties of the strands of Steady State Tokamak (SST-1), India which have been produced in an industrial scale has been used. Various necessary conditions for thermal stability, normal zone and quench characteristics have been investigated in the framework of this 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. Consequently, 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.
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Figure 2.1
Figure 2.2
Figure 2.3
Figure 2.4a
Figure 2.5
Figure 2.6
Figure 2.7
Figure 2.8
Figure 2.9
Figure 2.10

$E, \text{J/cm}$

$\eta^2$

Figure 2.10
Figure 2.11
Figure 2.12
Figure 2.13
Figure 2.14
Figure 2.15
Figure 2.16
Figure 2.17