Chapter 9

General conclusions and recommendations

The main issue of this thesis has been the influence of especially the interstrand- and boundary-induced coupling currents on the power loss, field homogeneity and stability of accelerator dipole magnets. The main conclusions of the thesis are presented in the final sections of each chapter.

In chapters 4 and 5 the coupling currents have been dealt with by means of a network model in which the strands are connected by contact resistances. General conclusions concerning the modelling of coupling currents are reviewed here and possible extensions and further improvements discussed.

It has been shown in chapters 6, 7 and 8 that most of the electrodynamic effects in a magnet, caused by the coupling currents, can be directly related to the contact resistance. In this chapter it is discussed how an optimum can be found for the contact resistances in order to limit undesired time-dependent effects without affecting the electromagnetic stability of the cable too much.

The contact resistances are determined by several parameters during the process from cable winding to excitation of the magnet. Recommendations are given for controlling the contact resistances and for measuring them on a single cable piece, in order to obtain accurate and representative values of the resistances in the coil itself.

Finally, it is briefly discussed how the results of the thesis can be applied to other types of cables and magnets.

9.1 Modelling of coupling currents in multistrand cables

Coupling currents in and between the strands of a superconducting Rutherford-type cable can be well calculated when the cable is modelled as a 3-dimensional network of nodes interconnected by strand sections and contact resistances. Two types of contact resistances are present in a cable: contact resistances R_a between adjacent strands and contact resistances R_c between crossing strands. Several network models have been developed in the past 20 years. Using these models it turned out that one type of current, called the interstrand coupling current (ISCC), is induced if the cable is subject to a varying field.

An improved model is described in detail in chapter 4 of which the main improvements are the possibilities to calculate the time-dependent behaviour of the coupling currents and to include many types of non-uniformities which are likely to be present in the cable of a coil. Calculations as a function of time can be performed since the mutual- and self-inductances between all strand sections are incorporated in the network model. The non-uniformities can be classified in four types, shown in Table 9.1.

Table 9.1. Survey of the causes of various types of non-uniformities in the contact resistances and the field-sweep rate which are present in a coil.

	Variations across the cable width	Variations over the cable length
Non-uniformities in the contact resistances	Variation in the transverse pressure on the cable Keystone of the cable Manufacturing tolerances	Soldered connections Strong variations of the transverse pressure in the coil ends Weak variations of the transverse pressure over the entire cable Manufacturing tolerances
Non-uniformities in the field sweep rate	Inherent to the magnet design, and present everywhere in the coil	Strong variations in the coil ends and the terminals Weak variations over the entire cable

All these non-uniformities are inherent to the cable and magnet geometries except for the manufacturing tolerances. These might lead to variations across the cable width as well as over the cable length. Especially local spots in the cable with smaller electrical contacts between the strands could strongly increase the coupling currents.

A detailed evaluation of the various non-uniformities in a cable has shown that besides the well-known ISCC a second type of coupling current is generated. These currents are induced during a field sweep due to the variations (or boundaries) in contact resistance and field-sweep rate along the cable length and are named '*Boundary-Induced Coupling Currents (BICCs)*'. Variations across the cable width do not cause BICCs but only change the ISCC-distribution.

Both types of induced currents differ with respect to the effective loop length, the characteristic time and the magnitude. The effective loop length of the ISCCs is equal to the cable pitch, whereas the BICCs can flow through large sections of the cable. The large loop length also leads to a characteristic time which can be one or more orders of magnitude larger than that of the ISCCs.

The magnitudes of the ISCCs and the BICCs in Rutherford-type cables are:

– proportional to the field-sweep rate $\dot{B}$ and especially its component $\dot{B}_\perp$ normal to the cable width,
– inversely proportional to the contact resistances R_a and R_c (or the root of the contact resistances in the case of BICCs with a small loop length).

The magnitudes of the BICCs usually increase for increasing *gradients* $d\dot{B}/dz$ (and especially the component $d\dot{B}_\perp/dz$), and $d(R_c^{-1})/dz$, with z the coordinate along the cable axis. This implies that in accelerator magnets the BICCs are mainly caused by the coil ends, where the cable bends around the beam pipe, which leads to a locally very small $\dot{B}_\perp$ over a length of the order of one cable pitch. Also the cable-to-cable connections between the two layers of a coil and the coil terminals, where the electrical contact between the strands is locally very small, will lead to large BICCs.

Both types of induced currents increase strongly for increasing cable width and twist length of the strands. In accelerator magnets, the cable width is restricted within a factor of about 2 in order to limit the inductance of the magnet. This implies that the cable width increases with increasing design operating field. Once the cable width is set, the cable pitch is also more or less fixed since the cable has to be mechanically stable. Hence, the coupling currents and consequently the time-dependent effects in the magnets become more pronounced with an increasing operating field of accelerator magnets. The main parameter by which the magnitudes of the ISCCs and the BICCs can be significantly changed is the contact resistance because the width and cable pitch are strongly correlated to the design field of the magnet. The magnitudes of the ISCCs and BICCs are especially influenced by R_c whereas R_a will only be relatively important if $R_a << R_c$ or if the field is applied parallel to the cable width.

It is shown in chapter 5 that the magnitudes of the BICCs and their characteristic times are also related to the effective strand resistivity that the BICCs 'see'. In the 1 m long LHC dipole model magnets the effective resistivity is deduced to be of the order of 10^{-14}-10^{-15} Ωm. The diffusion of the coupling currents from the contact points into the filaments of the strands as well as the exact current pattern of the coupling currents over the cross-section of a strand have to be investigated in order to understand this effective resistivity.

Modelling BICCs by means of a network model is much more time-consuming than modelling ISCCs. The reason for this is that the distribution of the ISCCs can be calculated for a given field change assuming that it will not vary in the *z*-direction. The actual ISCC distribution in the cable along the length can then be calculated by scaling the currents to the local field change.

Steady-state calculations of the ISCCs in single cables take just a few seconds CPU time on a 10 MFlops machine (for cables having 10-60 strands) and it takes still less than a few minutes for stacks of cable pieces or coils. The computing time required to calculate the time constants of the ISCCs depends strongly on the number of mutual inductances that are involved and hence on the number of strands in the cable and the number of cables in the stack or coil. The CPU time can be significantly reduced by decreasing the number of time steps and disregarding the mutual inductances between strands that are located at a relatively large distance from each other. The calculation of time constants, with an accuracy of about 10%, then takes usually less than a minute CPU time for a 40-strand cable and up to half an hour for an entire coil with about 40 turns wound from a cable having 30 strands.

In order to calculate the BICCs it is necessary to model the entire cable, which means that an array with about $5N_s^2$ variables per twist length has to be solved. In the case of practical coils, made of cables having typically 20-40 strands and with a length of the order of 10^2-10^4 times the cable pitch, this implies that millions of variables have to be solved. Steady-state calculations are possible but take hours of CPU time. Furthermore, the required large array sizes of up to several GByte are difficult to handle and, therefore, have to be split in smaller subarrays which have to be solved subsequently.

Evaluation of time-dependent effects requires large computing times especially for long cables having many strands. Because the characteristic time of the BICCs depends strongly on the longitudinal position in the cable (see section 5.4.3), more time steps have to be taken than in the case of ISCCs. Calculation of the characteristic time τ_{bi} of the BICCs in a 14-strand cable with a length of 10 times the cable pitch requires several minutes CPU time, while it already takes about an hour for a 26-strand cable with a length of 20 times the cable pitch. A good estimate of τ_{bi} in long cables can be obtained by extrapolating the results obtained on short cable pieces. In this way, the order of magnitude of τ_{bi} can be estimated, even for an entire coil, if of course the effective strand resistivity and the R_a-, R_c- and $\dot{B}$-distributions along the cable length are known.

Further extensions of the network model are possible with respect to the thermal behaviour and electromagnetic stability of the cable. The temperature in each strand section can be calculated in a similar way as the currents are calculated, if the thermal conductivity and the heat capacity of the conductor are known as well as the heat transfer coefficients between the strands and between the strands and the helium (inside and outside the cable).

The effect of the coupling currents on the electromagnetic stability of the cables requires the use of a non-linear *U-I* relation of the strands. In section 4.5 it is shown that the ISCCs could redistribute, without generating a larger power loss, as soon as one of the strand sections reaches the critical current. The impact of strand saturation, caused by the BICCs or a non-uniform current distribution, on the current distribution and the dissipated energy has to be investigated in order to improve the actual picture of stability in multistrand cables. The effect of strand saturation can be evaluated with the network model presented in section 4.2 without any further improvements.

The computing times for each simulation will be of the order of hours CPU time, since the currents for each time step have to be calculated iteratively (due to the non-linear *U-I* relation of the strands). A qualitative understanding of the influence of R_a and R_c on the electromagnetic stability can be obtained by modelling cables with a small number of strands.

The principle of the BICCs in combination with the geometry of the cable force that BICCs will not only occur in and between the strands of a cable but also in and between the filaments of the strands. The BICCs at strand level are not dealt with in this thesis since their impact on the performance of accelerator magnets is probably very small (like the impact of the interfilament coupling currents is small compared to that of the ISCCs). For other types of magnets, where R_a and R_c are large and the cable is exposed to large field-sweep rates, the BICCs within the strands could play a significant role.

9.2 Restrictions of the contact resistances

During a field sweep, the ISCCs and the BICCs affect the performance of the coil with respect to the power loss, field distortions and stability. Before winding a coil, the optimum R_a- and R_c-values have to be estimated, which lead to sufficiently small coupling currents during (de-)excitation of the coils.

- The effect of R_c on the interstrand coupling loss is dealt with in chapter 6. The R_c-value can be well specified if the maximum allowable dissipation is known, since the calculated and measured power losses correspond well.
- The effect of R_c on the field distortions caused by the coupling currents is dealt with in chapter 7. The main field distortions caused by the ISCCs in an accelerator dipole magnet are the normal-dipole, skew-quadrupole and normal-sextupole components. The minimum R_c can be calculated if the allowable field errors are specified, since the calculated and measured values of the above-mentioned field errors correspond within a factor 2. The field distortions caused by the BICCs vary sinusoidally along the magnet axis with a period equal to the cable pitch. Their magnitudes are hard to assess (since it is the net result of a superposition of the fields produced by numerous BICCs) but can easily become one order of magnitude larger than the errors caused by the ISCCs. The effect of sinusoidally varying field distortions on the particle motion is not well-known and has to be investigated in order to put constraints on the maximum allowable magnitude of the BICCs. At present it is thought that the influence of the BICCs on the particle motion is much smaller than that caused by the filament magnetisation and the ISCCs, as long as the integral value of the field distortion caused by the BICCs is much smaller than 10^{-4} T.
- Two effects are considered concerning the influence of R_c on the electromagnetic stability of the cable (see chapter 8):
  - The coupling currents (especially the ISCCs) cause an energy dissipation (or interstrand coupling loss, ISCL) which results in a temperature increase of the cable and, therefore, decrease the temperature margin of the coil. The temperature increase of the cable can be roughly estimated if R_c and the heat transport through the cable insulation are known.
  - The coupling currents (especially the BICCs) affect the current distribution among the strands which could locally saturate or quench the strands. The magnitude of the BICCs is difficult to predict but can be estimated by testing prototype magnets.

It is clear that the ISCL, the field distortions and the stability problems can be decreased by increasing R_a and R_c. This does reduce the coupling currents but, on the other hand, could also reduce the cryogenic stability of the cable against transient heat pulses, since:

– an increase in R_c can reduce the current redistribution among the strands in the case of a local transition in a strand section from the superconducting to the normal state,
– coatings, resistive barriers, solder and resin affect the thermal conduction and heat transport between the cable and the helium and can change the mechanical behaviour of the cable and could, therefore, change the process of frictional heating and heating in the cable surroundings.

Both effects are not dealt with in this thesis, since a profound treatment would probably take several years, but could play a role in the quench behaviour (i.e. in the training curve) of a coil in the case of small transient heat pulses. A certain optimum in R_c should be found for which the power loss, field errors and stability during ramping can be tolerated without affecting the cryogenic stability too much.

In the 1 m long LHC dipole model magnets no correlation is observed between the number of training quenches and R_c. However, the cables used in these magnets are quite similar with respect to the strand coating, and all have R_c-values between 1 and 6 μΩ. Hence, a correlation can still be present for cables with much smaller or larger R_c.

The above implies that it is preferable to wind *model and prototype coils* from cables having contact resistances which are just large enough to reduce the undesired effects related to the ISCCs (i.e. the effects which can be well predicted), instead of making them from cables having much smaller or much larger R_a and R_c. The testing of several model and prototype coils makes it then possible to estimate the magnitude of the BICCs and their effect on the stability and the field homogeneity of the magnet. Only if in the coming years:
– the effect of the contact resistances on the stability of the coil will be understood,
– the behaviour and magnitude of the BICCs become more clear and predictable,

it will be possible to specify R_a and R_c even before constructing the first models.

Of course, the coupling currents can also be reduced by decreasing the field-sweep rate during excitation. This implies an increase in the ramp time and therefore a decrease in the effective operating time of the accelerator. It should be investigated whether an increase in the excitation time would have an effect on the final luminosity at operating field.

The excitation procedure can be improved by using a variable field-sweep rate, being small at small fields, in order to limit the relative field errors. At intermediate fields the field-sweep rate can be larger while at large fields it should again be small, in order not to affect the stability too much.

The temperature increase of the cable due to the coupling currents cannot only be reduced by increasing the contact resistances or by reducing the field-sweep rate but, of course, also by improving the heat transfer through the cable insulation. The constraints on this improvement are that the cable insulation has to withstand the voltages that occur during a quench and has to be strong enough to avoid breakage during winding.

Accelerator magnets often have to be de-excitated with a high field-sweep rate in the case of a quench in one of the series connected magnets. A quench-back in other magnets during this fast de-excitation has to be avoided but can occur if the ISCL is large and the cooling of the cable is poor. Additionally, large BICCs will further enhance ramp-rate limitation (i.e.

reduce the critical field-sweep rate). The mechanisms that influence the ramp-rate limitation are discussed in chapter 8. The maximum de-excitation rate depends strongly on local variations in the power loss, cooling properties and BICCs and is therefore very difficult to predict and quench experiments on prototype magnets are necessary to determine this value as well as possible variations among the magnets.

9.3 Controlling and measuring contact resistances

Once the minimum R_a and R_c are specified, it has to be investigated how these values can be obtained. It is important that R_a and R_c should not only be limited but, preferably, also be more or less constant over the cross-section of the coils in a magnet. During excitation this reduces the unexpected field distortions whereas during de-excitation it reduces the possibility of having locally large energy losses. The R_a- and R_c-values should also be reproducible from magnet to magnet in order to facilitate the field-correction methods during excitation.

The contact resistances depend on various parameters (see section 4.3), and in particular on:
- the pressure on the cable,
- the type of coating,
- the strand deformation,
- the surface conditions and level of oxidation of the strands,
- the temperature and pressure cycle during coil manufacturing.

Large differences in R_c of several orders of magnitude are observed if the above-mentioned parameters are changed. Therefore, the requirement of reproducible R_a and R_c among the magnets in an accelerator implies that all the strands and cables have to be produced, stored and processed by identical and well-controlled methods. Furthermore, also the prestress and the curing cycle have to be the same for all the magnets.

In accelerator magnets the Rutherford-type cables are highly compacted and often keystoned in order to attain a high overall current density and to improve the uniformity of the coils, which is important to reduce training. The high compaction factor causes a large deformation of the strands and hence a large contact area between the strands which reduces the contact resistance. The keystoning of the cable probably causes a variation of R_a and R_c over the cable width, resulting in the smallest resistances near the smallest edge of the cable. The magnitude of the ISCCs and the ISCL is dominated by R_a and R_c in the *centre* of the cable, and are, therefore, almost not affected by the keystone angle.

R_a and R_c can be changed by means of strand coatings or intrastrand barriers. The use of an (additional) resistive barrier between the two layers in the cable enables to vary R_a and R_c independently. Thin sheets of, for example, stainless steel or nickel increase R_c significantly and could make R_c more predictable and reproducible.

A first estimate of R_a and R_c of a cable can be obtained by means of the *UI* method (see section 4.10.3) performed on a short cable piece. The method is cheap and fast but unfortunately quite sensitive to local variations in the contact resistances. Once an idea is formed about the type of strand and cable, which would lead to the desired R_a and R_c, a more accurate determination of the global R_a and R_c should be made by means of the calorimetric method (see section 4.10.2) on a short sample with a length at least equal to the cable pitch.

For both methods it is important to determine R_c on a cable piece which is and has been exposed to the same pressure and temperature cycle as will the cable in the total process from manufacturing, winding, cool-down and operation. Results of measurements have demonstrated that R_c in a coil is, in first approximation, independent of the temperature (between 1.9 and 4.3 K), the magnetic field and the Lorentz force on the cable during operation.

9.4 Effect of coupling currents in other magnets

Detailed knowledge of the electrodynamic properties of the cable are essential for magnets, wound of large-size cables, which need to have a high field homogeneity (such as beam-guiding magnets), or are subject to a large field-sweep rate (such as fusion magnets, pulsed SMES systems and AC generators). The emphasis in this thesis is on Rutherford-type cables as used in accelerator dipole magnets, but a similar analysis of the electrodynamic properties can be made for other types of magnets as well.

For all *coils made of Rutherford-type cables*, the formulas at strand and cable level remain unchanged. The steady-state ISCCs and ISCL in each turn of a coil can be calculated by using the expressions given in section 4.4.1, while the time constants of the ISCCs in a cable and stack cables are given by eqs. 4.31 and 4.39. The total ISCL in the coil is obtained by summation over all the turns. The field errors caused by the ISCCs can be calculated using the approach given in section 7.2. By doing so, both the ISCL and the field caused by the ISCCs can be estimated within about 20% (for given R_a and R_c), which is often smaller than the accuracy by which the contact resistances are determined.

A qualitative estimate of the BICCs can be made according to the expressions given in sections 5.4.2-5.4.4 and the approach given in section 5.4.5. However, since the cause and the magnitude of the effective strand resistivity are both unknown, it remains necessary to test model magnets to quantify the BICCs and their effect on the magnet performance.

For *coils made of other types of cables*, the discussion of the interfilament coupling and filament magnetisation remains unchanged. The different internal configuration of the cable requires a same type of modelling, however with a different cable-specific network, in order to calculate the ISCCs and BICCs. Hence, the network model as discussed in section 4.2 has to be modified accordingly. In general, the expressions for the coupling currents, power losses and time constants will be qualitatively similar but quantitatively different due to the different geometry.

Fig. 1.3 can be well used as a guideline in the design of cables and magnets of which the performance is susceptible to coupling currents, power losses and field distortions, or magnets of which the operation margin is likely to be strongly reduced due to coupling currents and power loss.