Chapter 1

General introduction

Since the discovery of materials that remain superconductive up to high-magnetic fields, the number of successful applications has increased considerably, in particular in the field of superconducting magnets. Together with the increase of the stored energy of large magnet systems, the size of the conductor also increased from single wires to large cables. This thesis deals with the consequences of the multistrand configuration of the cables on the electrodynamic properties of magnets.

In this first chapter the main applications of superconducting magnets are presented and the relevance of this thesis for the various applications is demonstrated. The emphasis is on accelerator magnets made of multistrand cables since the electromagnetic stability and field homogeneity of this type of magnet are strongly influenced by the cable configuration.

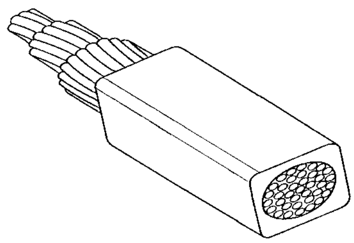
An introduction to the main electrodynamic effects in cables is presented. A change in the external magnetic field acting on a superconductor causes several types of induced-current patterns. Important issues are persistent currents in the filaments, interfilament coupling currents, interstrand coupling currents and boundary-induced coupling currents. The influence of these currents on the performance of the magnet with respect to power loss, field distortions and electromagnetic stability is discussed.

1.1 Introduction to the electrodynamic properties of superconducting cables and magnets

Superconducting magnets are often used to produce high-magnetic fields and fields in large volumes where the use of conventional magnets would result in a large consumption of electric power. In magnet systems with a large stored energy the electrical conductors, from which the coils of the magnets are made, usually consist of multifilamentary strands arranged in cables. The main reason for using cables is the need to limit the quench voltages (see section 2.2.6). The filaments are made of superconducting alloys, in particular NbTi and Nb_3Sn, and are embedded in a normal conducting matrix thus forming strands. Usually, the strands as well as the filaments are transposed with certain twist lengths. The following two types of cables are the most commonly used:

- Rutherford-type cables (see Fig. 1.1a) are manufactured by flattening hollow tubular multistrand cables, which are compacted by rolling to packing factors of up to 90%. The large compaction not only increases the overall current density but also reduces the average contact resistance between the strands, which will be shown to be an important parameter in the magnitude of the coupling currents. In accelerator magnets the cables are electrically insulated and cooled by means of bath cooling. The characteristics of these cables are dealt with in more detail in section 2.3.

a



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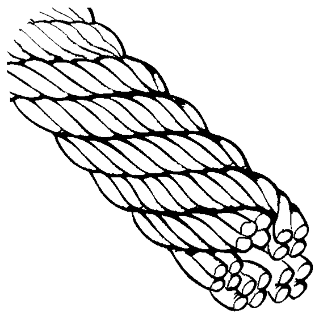

c

Figure 1.1. **a.** 11-strand Rutherford-type cable.
b. Cable-in-conduit conductor.
c. Cable made of five twisted subcables, each of them having four twisted strands.

- The cable-in-conduit conductor (see Fig. 1.1b) consists of a large number of strands or sub-cables which are wrapped inside a jacket (usually made of stainless steel) for mechanical reinforcement. The cable is often cooled by means of forced flow cooling, which implies that the helium is forced through the voids in the cable, which enhances the stability of the cable.

Various other types of cables exist, which differ mainly with respect to the number of subcables and strands, the amount of stabiliser, the type of cooling etc. As an example, a cable without a jacket, made of several subcables with twisted strands is shown in Fig. 1.1c. A general treatment of the design and fabrication of NbTi conductors can be found in the literature, for example in [Collings, ’86].

If multistrand cables are exposed to a changing magnetic field, various currents are induced. These currents flow not only within the individual strands of the cable but also in and between the various strands of the cable. The latter increase considerably for an increasing size of the cable, similar to eddy currents in a normal conducting bar.

The main question to be clarified in this thesis is: *How do the induced currents, and in particular those currents flowing in and between the strands, affect the performance of superconducting magnets?* This influence is investigated with respect to:

- The energy loss inherent to the currents flowing through resistive parts of the strands or the cables. The energy loss leads to an additional heat load (at the operation temperature of the magnet) which has to be compensated by the cryogenic system. The effect is important for almost all magnets and in particular for those which are subject to large field variations.
- The field distortions caused by the currents. Especially in accelerator magnets, field distortions are a major concern since the particle motion becomes more unstable at larger field errors, which leads to enhanced beam losses and a reduced luminosity.
- The temperature margin and electromagnetic stability of the cable. Due to the energy dissipation, the cable warms up locally so that the difference between the transport current and the critical current decreases. The effect is especially important in magnets with poorly cooled cables. Additionally, the induced currents cause a non-uniform current distribution between strand sections in the cable so that some strand sections carry a total current which is larger than the transport current. This could directly lead to local saturation of a strand section and possibly a quench. Indirectly, a non-uniform current distribution locally limits the difference between the total strand current and the critical strand current and therefore reduces the electromagnetic stability of the cable.

Four types of induced currents can be distinguished which differ with respect to the part of the conductor through which they flow, the characteristic loop length and the characteristic time.

- Persistent currents (PCs) in the filaments (partially) shield the interior of the filaments against the external applied field. The magnitude of these currents depends on the field and the field history but, in first approximation, not on the field-sweep rate.
- Interfilament coupling currents (IFCCs) are induced by an external field variation and flow between and in the filaments of a strand. The magnitude of the IFCCs increases with increasing twist length of the filaments and decreasing resistivity of the matrix

material. The IFCCs have a characteristic loop length equal to the twist pitch of the filaments, exhibit time constants of typically 0.01 to 0.1 s and cause the interfilament coupling loss (IFCL).

- Interstrand coupling currents (ISCCs) are also induced by an external field variation and flow between and in the strands of the cable. The magnitude of the ISCCs increases with increasing twist length of the strands and decreasing electrical contact resistance between the strands. The ISCCs have a characteristic loop length equal to the twist pitch of the strands, exhibit time constants of typically 0.01 to 10 s and cause the interstrand coupling loss (ISCL).
- Boundary-induced coupling currents (BICCs) are mainly induced by variations of the field-sweep rate and the contact resistances along the length of the cable. BICCs can flow in and between the strands of a cable and also in and between the filaments of the strands. Only the former type of BICCs are dealt with in this thesis. The loop length and the characteristic time of the BICCs can be several orders of magnitude larger than those of the ISCCs. The additional power loss caused by the BICCs is dissipated in the contact resistances between the strands and is regarded in this thesis as an enhancement of the ISCL.

The characteristics of the currents are briefly surveyed in Table 1.1.

Table 1.1. Survey of the various currents and losses being present in a cable with non-insulated strands which is exposed to a varying field. The decay times represent characteristic times during which the currents decay once the driving force that has induced them becomes 0.

Currents	Loss	Location	Characteristic decay time
PCs	Filament magnetisation	In the filaments	$\rightarrow \infty$
IFCCs	Interfilament coupling loss (IFCL)	In and between filaments	0.01-0.1 s
ISCCs	Interstrand coupling loss (ISCL)	In and between strands	0.01-10 s
BICCs	(Included in the ISCL)	In and between strands	$>10\text{-}10^5$ s

The persistent currents and interfilament coupling currents have been an important issue of research during the recent decades (and still are). Their properties are now well understood. The ISCCs have been investigated since the seventies and have become more and more important because the size of the cables has increased considerably. Qualitatively, the ISCCs are now more or less understood. Much research is still being carried out on the quantitative understanding of the ISCCs, which is a complicated matter since the value and the distribution of the contact resistances between strands, which determine the effective loop area's and the magnitude of the ISCCs, depend on many parameters (see section 4.2).

However, since the use of larger cables, anomalous time-dependent effects are often observed which could only be partially explained by the presence of ISCCs. In this thesis the existing models for the calculation of strand currents in superconducting cables are improved in order to investigate in more detail the time-dependent behaviour of cables in magnets. This has not only resulted in a realistic model of the ISCCs but has also led to the description of a new type of current, the so-called 'boundary-induced coupling current'. This name indicates that these currents, which are induced by a varying field, are created due to boundaries especially those between local variations in the contact resistances and field change.

It is clear from the above that the influence of the coupling currents on the electrodynamic properties of a magnet is crucial for many magnets, made of multistrand conductors, if:

– the cables are exposed to large field changes,
– a homogeneous magnetic field in the aperture is required,
– the cables are poorly cooled.

In section 1.3 a brief survey of the main applications of magnets is given, showing for which magnets the performance is likely to be strongly affected by the coupling currents.

1.2 Superconducting magnets

In the late fifties, a new class of materials was discovered which exhibits superconducting properties up to high magnetic fields. The most important of this class are NbTi and Nb_3Sn with critical fields of about 11 and 21-28 T respectively (at 4.2 K).

Small solenoid magnets were developed in the sixties. However, large fields could not be achieved due to the poor electromagnetic stability of the conductors. The development of the multifilamentary conductor in the seventies was an important step towards larger current densities at higher fields. These conductors, with diameters in the range of 0.1-1 mm, consist of superconducting filaments embedded in a normal conducting matrix. In large magnet systems many wires are bundled together to form multistrand cables, mainly in order to limit the inductance and the voltage levels. Nowadays, most applications of high-field magnets are based on coils wound from cabled superconductors.

The main applications of superconducting magnets are enumerated here. More detailed information can be found in the literature, for example in [Foner, ’81], [Wilson, ’83].

- **Solenoids.** These magnets are in use for general research at fields up to 20 T and bores up to 200 mm. The small solenoids are made of superconducting wire while the larger coils are wound from cables. High-field solenoids with a high field homogeneity are part of, for example, **NMR** (Nuclear Magnetic Resonance) spectrometers.

- **Magnets for nuclear fusion.** Power production on the basis of controlled thermonuclear fusion is feasible only by means of superconducting magnets since the use of conventional magnets is not economical. A magnet system of a tokamak mainly consists of DC toroidal field coils, enclosing a plasma ring, and pulsed transformer coils, for resistive heating of the plasma by inducing plasma currents. Both types of coils are made of large cable-in-conduit (CIC) conductors with forced-flow cooling. Although the toroidal coils carry a constant current during normal operation, which results in a constant self-field, they are also exposed to the changing field from the transformer coils. Not only the transformer coils but also the toroidal coils are therefore subject to large field-sweep rates of 0.1 Ts^{-1} (under normal operation) and up to 10 Ts^{-1}. (in the case of plasma disruption).

- **Magnets for high-energy physics.** Superconducting magnets are part of the accelerator itself, for guiding the beam, as well as of the detectors of the physics experiments. In section 1.3 the beam-guiding magnets are discussed. Large detector magnets are applied to determine the momentum of charged particles from the curvature of the track. They often enclose a considerable part of the chamber volume of the detector and can therefore have diameters of several meters. The coils are made of Al-stabilised Rutherford-type conductors and are slowly ramped to the DC operating field of typically 1-4 T in the centre to 1-6 T in the windings.
- **Magnetic Resonance Imaging (MRI).** Superconducting MRI magnets are in use for medical diagnostics and were first developed in 1980. The higher image resolution due to the larger field, is the main reason that nowadays most MRI magnets are superconductive instead of normal-conductive. The magnets exhibit a high stability and field uniformity in time. MRI magnets are made of wires and are slowly ramped to nominal field.
- **Superconducting Magnet Energy Storage (SMES).** Superconducting coils can be applied as an inductive energy storage. Large SMES systems (with stored energies in the order of GWh's) are studied for load-balancing in existing power grids. The power oscillation in long power lines can be stabilised by means of pulsed SMES systems, while voltage failures in power lines are already made up with small SMES systems (with a stored energy of 1-10 MJ).
- **Magnetic levitation (MagLev).** Magnetically levitated transportation systems can be realised with superconducting coils, since light-weight high-field magnets are favourable. The levitation is achieved by the repelling force between the superconducting magnets in the vehicle/train and eddy currents on the track.
- **DC motors and AC generators.** The main characteristics of superconducting generators and motors are the high efficiency, high power rating and reduced size compared to conventional motors. Superconducting coils can be part of the field windings and the armature windings. The steady increase of the development of AC superconductors enables the manufacturing of fully superconducting machines.
- **Magnetic separation.** Ferromagnetic and paramagnetic particles can be separated from a large non-magnetic mass stream of material by a magnetic force. The field gradient and efficiency can be greatly improved using superconducting magnets.
- **Magnetohydrodynamic power generation (MHD).** An ionised hot gas is passed through a channel with a transversely applied magnetic field. The corresponding voltage on the wall of the channel causes a current through an external load.

The main applications of superconducting magnets are surveyed in Table 1.2 where the magnets are characterised with respect to the usual geometry of the conductor, maximum field in the windings, field accuracy and field-sweep rate. The geometry is represented by a W for a single wire, RC for a Rutherford-type cable, CIC for a cable-in-conduit conductor and C for a cable without jacket. Some magnets, of course, have been manufactured with different design fields or from other types of cable than those mentioned in the table.

Table 1.2. The main characteristics of superconducting magnets. W = wire, RC = Rutherford-type cable, CIC = cable-in-conduit, C = cable without jacket.

Application		Conductor	Max. field on cond. [T]	Field accuracy	Field-sweep rate [Ts^{-1}]
Solenoids	Small bore	W	20	Medium	10^{-2}
	Large bore	C	15	Medium	Small
NMR		W	20	High	Small
Fusion	Toroidal coil	CIC	13	Low	0.1-10
	Transformer coil	CIC	13	Low	0.1-10
High-energy physics	Beam-guiding	RC	12	High	10^{-2}
	Detectors	C	6	Medium	Small
MRI		W	0.5-2	High	10^{-3}
SMES	Pulsed	C, RC	5-10	Low	10^{3}-10^{4}
	Low frequency	C, RC	5-10	Low	Small
MagLev		RC	5	Low	Small
DC motors		RC	2-5	Low	Small
AC generators		RC	2-6	Low	10
Magnetic separation		C	8	Low	Small
MHD		RC	8	Low	Small

According to the conclusion at the end of section 1.1, coupling currents can especially affect the performance of fusion magnets, beam-guiding magnets for accelerators, pulsed SMES systems and AC generators. In this thesis the emphasis is on the electrodynamic properties of multistrand conductors in accelerator magnets, and especially in LHC dipole magnets because of the severe restrictions with respect to losses during ramping, stability and field homogeneity. A brief introduction to accelerator magnets is given in the next section.

1.3 Accelerator magnets

The desire for investigating matter and forces between elementary particles has encouraged physicists and engineers to construct devices for accelerating particles to higher and higher energies. This started around 1930 with small rectifier generators and cyclotrons and later with betatrons, linacs and synchrotons.

Circular machines require mainly dipole magnetic fields to keep the beam of particles on the equilibrium orbit and quadrupole magnetic fields to focus and defocus the beam around the equilibrium orbit. Furthermore, there is a need for higher-order magnetic fields to correct field distortions and chromaticity. As the particle energy is proportional to the bending radius, the size of the accelerators has become larger and larger. In parallel, the linear dependence of the particle energy on the field strength of the dipole (bending) magnets has pushed the magnetic field to higher values.

For decades normal-conducting magnets have played an important role with fields up to 2 T, limited by the saturation of the iron. The breakthrough came with the construction of the Tevatron at Fermilab in 1983 [Cole, ’79]. Here it was shown that a large number of dipole magnets (with a central field of 4.4 T) and quadrupole magnets (with a field gradient of 75 Tm^{-1}) can be built, having a high quality and a good reproducibility.

After the Tevatron, other projects were approved, in which the design of the magnets was further improved. This has led to the construction of HERA in 1991 (with a dipole field of 4.7 T) [Wiik, ’85], and the design of the Relativistic Heavy Ion Collider RHIC (3.5 T) [Ozaki, ’90], the Accelerating and Storage Complex UNK (5 T) [Balbekov, ’83], the Superconducting Super Collider SSC (6.6 T) [Edwards, ’90] and the Large Hadron Collider LHC (8-10 T) [LHC, ’91/’93].

In order to store an intense beam of particles, a high field quality is necessary. For normal conducting magnets this requirement can be quite easily attained since the field is determined by the shape of the iron yoke. In the case of superconducting magnets the field is governed by the geometry of the coils, a precise arrangement which is difficult to control, and by the persistent currents and coupling currents, as discussed in section 1.1.

The coils of all main accelerator magnets are made of Rutherford-type cables to enable an accurate coil winding and to have a high overall current density while keeping the inductance small. A survey of the geometry of the cables as used (or foreseen to be used) in various accelerator dipole magnets is given in Table 1.3.

Table 1.3. Survey of the geometry of the Rutherford-type cables (envisaged to be) used in several accelerator dipole magnets with a two-layer cos(θ) configuration (see section 2.2).

Institute	Accelerator	Central field [T]	Operating Temp. [K]	Coil	Nr. of strands	Width [mm]	Av. height [mm]
BNL	RHIC	3.5	4.6	[a]	30	9.7	1.17
Fermilab	Tevatron	4.4	4.6	inner	23	7.8	1.26
DESY	HERA	4.7	4.5	inner	24	10	1.48
				outer	24	10	1.48
IHEP	UNK	5.0	4.6	inner	19	8.7	1.63
				outer	19	8.7	1.63
SSCL	SSC	6.6	4.35	inner	30	12.3	1.46
				outer	36	11.7	1.16
CERN	LHC, 1st design	10	1.9	inner	26	17	2.25
				outer	40	17	1.48
	LHC, 2nd design	8.4	1.9	inner	28	15	1.89
				outer	36	15	1.47
Nb_3Sn model dipole magnets for the LHC, 1st design							
CERN/ELIN [Asner, ’90]		10	ca. 4.3	inner	24	16.8	2.44
				outer	36	16.8	1.63
CERN/UT [Ouden, den, ’94]		11.1	ca. 4.3	inner	33	21.7	2.23
				outer	33	17.7	1.73

[a] This magnet has a single-layer cos(θ) geometry.

The increase in field is related to the cable dimensions as depicted in Fig. 1.2. It will be shown in chapters 4 and 5 that many effects related to the coupling between strands are strongly enhanced by an increase in the cable width. The figure shows therefore clearly that in circular accelerators the electrodynamic properties of the cable become more important with increasing field strength, i.e. usually increasing collision energy.

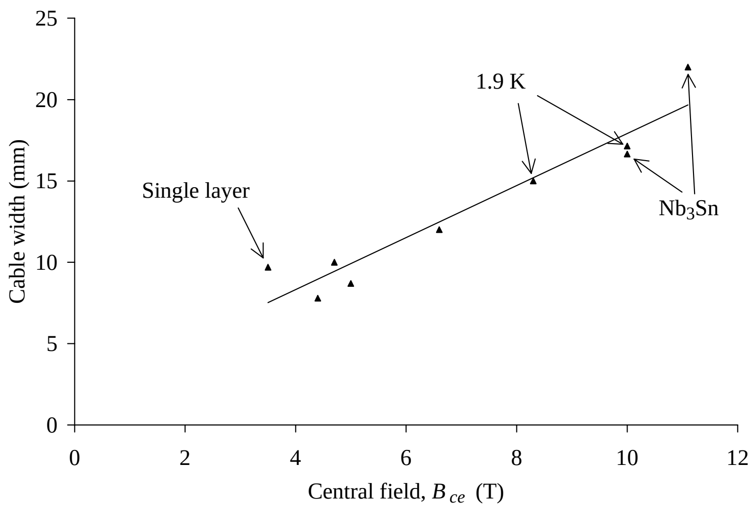

Figure 1.2. The width of Rutherford-type cables as a function of the design value of the central field of the dipole magnets (in which they are used). The operating temperature is about 4.3 K unless otherwise indicated.

On 16 December, 1994 the LHC was approved by the CERN member states to be the future accelerator to investigate mainly hadron physics, while also ion-ion and electron-proton collisions are envisaged. The LHC will be constructed in the same tunnel as the Large Electron Positron (LEP) machine, which came into operation in 1989. In LEP electrons and positrons are brought into collision whereas in LHC two proton beams will collide. The collision energy of LEP is limited to about 200 GeV caused by the synchrotron radiation that the particles emit as they are bent. In the case of protons the synchrotron radiation is much smaller and the collision energy is limited by the field produced by the bending magnets.

In two separate magnetic channels, two beams of particles with an equally signed charge and the same velocity, in the opposite direction, are brought into collision. This is accomplished by a novel design, that consists of two separate coil systems within the same mechanical structure (see section 2.2). The so-called 'twin-aperture structure' not only reduces the size of the magnets (compared to two single-aperture magnets) but probably results as well in a total cost savings of about 25%.

Superconducting dipole magnets with operation fields of about 8.4 T will be used in the LHC and result in a collision energy of about 14 TeV, about a factor 70 larger than in LEP. The maximum field of the magnets is about 10-20% larger to allow for adequate margins covering energy dissipation in the coils and production tolerances.

1.4 Scope of the thesis

This thesis consists of the following four parts which are illustrated in Fig. 1.3.

- In chapter 2 an introduction to accelerator dipole magnets is given. It is shown which aspects that are inherent to the cable and magnet design, influence the various currents as given in Table 1.1. A survey of the magnets, of which the electrodynamic properties are evaluated in chapters 6, 7 and 8, is presented. Also a survey of the main characteristics of the cables, from which the coils of these magnets are made, is given.
- In chapters 3, 4 and 5 the persistent currents and coupling currents in the strands and cables are dealt with as well as the loss related to these currents.
  - In chapter 3 an actual picture of the electrodynamic properties of single strands is presented in terms of filament magnetisation and interfilament coupling currents, which are both experimentally investigated on several LHC cables.
  - In chapter 4 the interstrand coupling is discussed. The network model, by which the cable is simulated and by which the ISCCs are calculated, is dealt with in detail. The contact resistances R_a and R_c between adjacent and crossing strands are introduced which will play a dominant role in all subsequent chapters. An important issue is the dependence of R_c on the transverse pressure on the cable.
  - In chapter 5 the influence of longitudinal variations in the contact resistance and the field-sweep rate are dealt with. These variations are, in particular, present near the cable-to-cable connections and in the coil ends and provoke a new type of current, the ‘boundary-induced coupling current (BICC)’. The BICCs are described in terms of their magnitude, characteristic length, propagation velocity and characteristic time. The presence of BICCs in multistrand cables is demonstrated by analysis of the self-field of a 1.3 m long straight Rutherford-type cable.
- In chapters 6, 7 and 8 the effect of the coupling currents on the electrodynamic properties of accelerator magnets is investigated, in terms of:
  - the losses during ramping (chapter 6),
  - the field distortions (in the aperture of the magnets) caused by the coupling currents (chapter 7),
  - the ramp-rate limitation of the magnets, which is influenced by the coupling currents (chapter 8).
- In chapter 9 general conclusions are presented concerning the modelling of coupling currents and their impact on the performance of superconducting magnets. Recommendations are given for measuring and controlling the contact resistances in cables in the process from cable manufacturing to magnet operation.

Fig. 1.3 shows two dotted links. One of them concerns the field distortions due to the persistent currents which are not discussed in this thesis because it is a well-known phenomenon. The other one concerns the enhancement of the ISCL due to the BICCs which is dealt with in chapter 5 in the case of a single cable but is disregarded in chapter 6 in the case of a magnet. The increase is namely hard to assess and, where a dipole magnet is concerned, probably small compared to the coupling loss produced by the ISCCs.

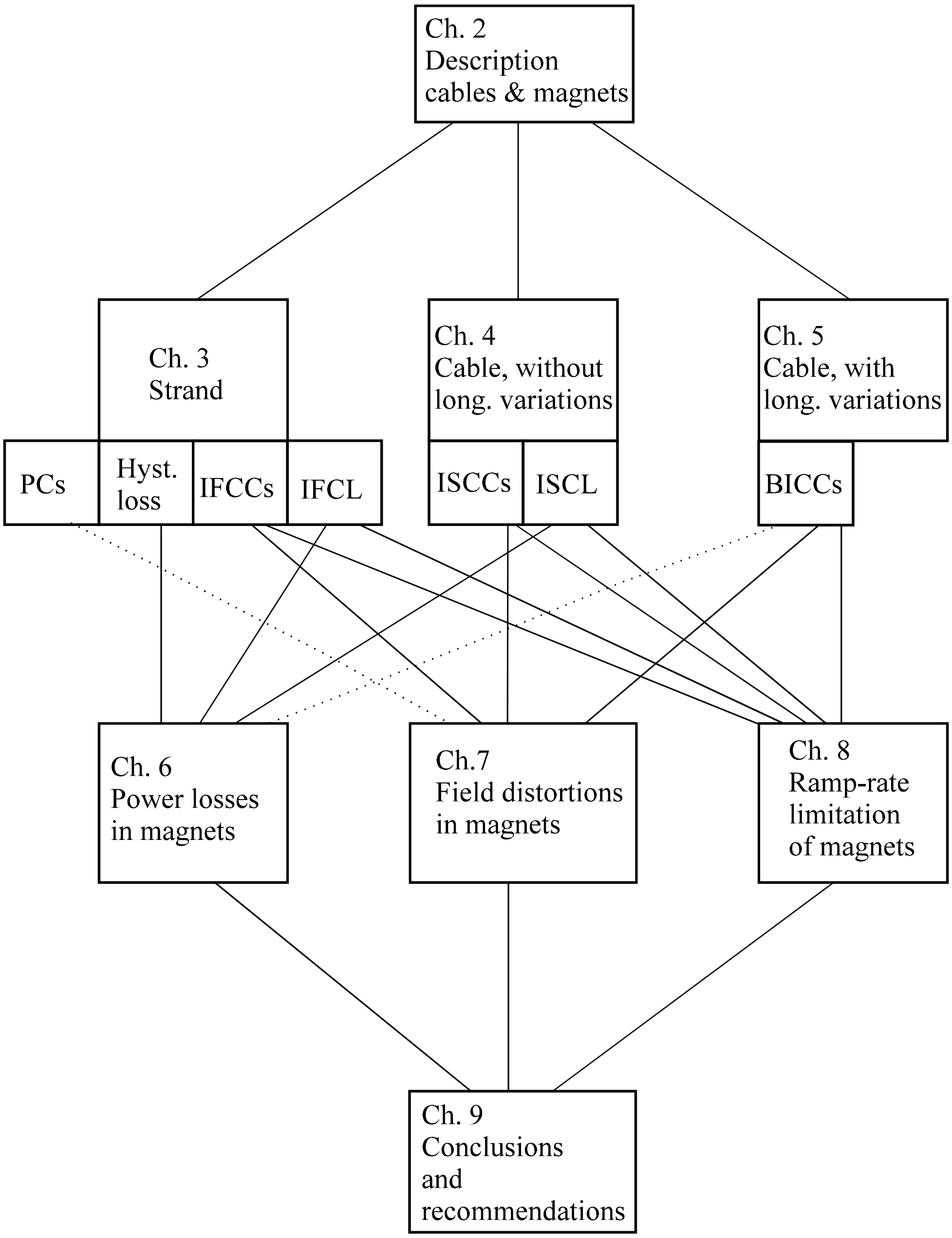

Figure 1.3. Schematic outline of the thesis, showing how the persistent currents, the coupling currents and the power losses at strand and cable levels affect the electrodynamic properties of superconducting magnets. The dotted lines are links that are present in a magnet but not discussed in the thesis.