Current Distribution Measurement in CICC Cables

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Abstract

The current distribution in the Cable In Conduit Conductor (CICC) cables has a relevant impact on the cable stability margin. Therefore in the research & development and testing phases of such cables, the study of the current profile behaviour under various operating conditions is a quite important issue.

As a matter of fact, CICC cables could be designed by assuming that the current is evenly shared among the strands; however in actual operating conditions, some regions of the cable may be interested by anomalous distributions, leading to possible local current sharing regimes, and eventually to the premature quench of the cable with currents lower than the expected critical figure. The complete physics grasp of such phenomenon is not yet clear, and a number of experimental and theoretical studies aimed at clarifying it are currently under progress [1, 2].

Introduction

Unfortunately, due to technical reasons, it is not possible to carry out direct current measurements neither in the single strands nor in the highest level macro strands (the so-called “petals”; see Fig. 1). An alternative solution could be to estimate the current distribution from indirect information; starting from external measurements, and in the frame of a pre-defined current representation base, the “best” approximation to the current density profile in terms of the selected base will provide the desired estimate. One of the most common approaches to get the indirect information is based on the adoption of Hall probes placed around the cable to measure the magnetic field, and on the adoption of a suitable technique of “inverse” problem resolution to determine the current distribution inside the cable.

Unfortunately, as typical in the case of inverse problems, the mathematical model to be inverted can be affected by ill-conditioning issues. In this case, the solution will result sensitive to all the model uncertainties and measurement errors; in addition, depending on the characteristics of the representation basis, the solution can show poor smoothness properties. It follows the need to use quite accurate data and quite robust models, eventually adopting additional suitable regularization techniques.

In the following, a possible approach to the current reconstruction inside CICC cables will be presented from a theoretical point of view, and the results achieved in some reconstruction experiments will be presented and commented. In particular, a detailed discussion of either the choice of representation basis, and of the regularization techniques adopted, including the necessary “calibration” experiments for results validation, will be discussed.
Cable Schematization

In principle, the current reconstruction process from magnetic measurements in CICC cables could be able to provide the current in all the possible details, as far as in each of the cable strands. As typical in inverse problem strategy, a “direct” solver has to be available. In the strands current case, the direct solver, able to compute the external magnetic field from each strand current, is conceptually trivial, as it reduces to a plain integration of Ampere’s law; however, in practice, due to the actual complex stranded geometry of the cable, such a computation may reveal a bit cumbersome. Moreover, the “inverse” problem of determining the currents from the magnetic field measurement could be severely ill-posed.

As a matter of fact, in the hypothesis that no ferromagnetic material is present in the system, the relationship between the strand currents and the magnetic field measured by the probes around the cable is linear, and can be represented through a suitable Green function, which depends on the geometry of the strands and on the magnetic probes position and alignment. In practice, the actual number of probes is much lower than the number of strands; the mathematical model is consequently largely undetermined. In addition, most of its singular value fall inside the uncertainty range, determined by either the measurement noise and, more consistently, by the uncertainty on many geometrical parameters. It is then necessary to represent the current distribution inside the cable in a highly simplified way, characterized by a few parameters, that will become the unknowns of the reconstruction procedure. It should be noticed that also from the point of view of the problem regularization, it may turns profitable that the number of unknowns is less than the number of equations (i.e. the probes), and the solution to the problem is approached through a pseudo-inversion of an over-determined linear system. On the other hand, the resolution attainable in the representation of the current distribution depends on the number of unknowns adopted. Therefore, after having fixed, as a general rule, the number of measurements to the largest possible amount, the choice of the number of unknowns comes out from a trade off between the resolution and regularity requirements on the solution.

A quite reliable solution could be to chose as the representation basis a set of the model eigenfunctions. However, the simplest while effective solution is a “piecewise constant” representation: the cable cross section is subdivided in a number of “tiles”, each interested by a flat current density. Of course, the regularity of such a solution is rather poor. Smoother solutions could be also attained by adopting a more sophisticated representation in each tile, e.g. a bi-linear or parabolic profile, and imposing continuity at the tile boundaries. Conversely, the interpretation of such currents can be related to the highest level bundle of strands (the “petals”), and they will be referred in the following as “petal currents”.

Coherently with the exposed hypothesis, and exploiting the system linearity, the magnetic model for the system at the generic cable cross section can be described by the following equations system:

$$ Gi = b - b_e $$

where $i$ (dim $i = N_c$) is a vector of $N_c$ real numbers representing the petal currents on the cable cross section; $G$ (dim $G = N_m \times N_c$) is the Green matrix linking the currents vector $i$ and the flux density component at the probes positions; $G_{ij}$ gives the magnetic field measured by the $i$-th probe produced by a unit current corresponding to the $j$-th component in the vector $i$; $b$ (dim $b = N_m$) is the vector of overall flux density measured by the probes; $b_e$ (dim $b_e = N_m$) is the vector of flux density measured by the probes and due to the external (known) field sources only.

Impact of the uncertainties

Due to a number of geometrical uncertainties, the Green matrix should rather be written as $(G + \Delta G)$; in addition, the measurement vectors should be written as $(b + \Delta b)$ and $(b_e + \Delta b_e)$ because of the measurement uncertainties; therefore the actual equations system is:

$$ (G' + \Delta G') k = b - b_e + (\Delta b - \Delta b_e) $$

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The evaluation of the unknown vector $\mathbf{k}$ requires the (pseudo) inversion of the system matrix. In particular, due to the over-determined nature of the system, the solution can only be sought in a weak form. In the specific application described in this paper, the weak solution has been found by minimising the quadratic norm of the residual errors vector through a pseudo-inversion technique. Of course, the reliability of the available measurements hardly impacts on the reconstruction quality. A quite effective way of reducing such uncertainties is to perform a number of experiments in which a suitable set of the current distributions (flat and, possibly, not flat) can be assumed as known. Then the geometrical data of the mathematical model are adjusted until the actual current distribution is obtained by the reconstruction procedure.

As a test case, the results obtained in the course of the testing of the busbars systems of the Toroidal Field Model Coil (TFMC) are reported. See fig. 3 for a picture of the Hall Probes assembly around the bus bar before insertion in the TOSKA facility. The experiment has been performed at Forschungzentrum Karlsruhe in 2002, in the framework of European Fusion Development Agency (EFDA) activity for the development and design of the ITER tokamak. In figure 2 are reported the values of the magnetic field around a straight section of the busbar measured by tangential and radial Hall probes, after the adjustment of the geometrical parameters in order to obtain the best fit of the uniform current distribution.

**Regularization strategy**

A quite effective way to regularize linear ill-posed problems such as (1) or (2) is to adopt matrix pseudo-inversion techniques based on the Truncated Singular Value expansion. The procedures retains only singular vectors associated with singular values higher that the uncertainties on the data. An effect of such regularization strategy is reported in figure 4, where the reconstructed petal currents for the same experiment, but with different number of singular values, are reported.
Examples of current reconstructions

A few examples of current reconstructions are reported here, related to a resistive experiment (figure a), to an experiment with a maximum current of 10kA (figure b) and to an experiment with maximum current of 69kA (figure c). Note how the petal currents keep flowing after the net current shuts down, due to the presence of “loops” closing at petals connections (figure d).

![Graph](image)

Figure 5 – Examples of current reconstructions.

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