Summary of Doctoral Thesis

Numerical Modelling of Superconducting Components Applied in the Devices for High Energy Physics

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Superconductivity is a phenomenon widely applied in the devices for high energy physics. Unique properties of the superconducting state, especially zero electrical resistance and perfect diamagnetism, promote the application of such materials to produce and control strong magnetic fields. Such abilities are crucial in particle accelerators, currently the most important machine used in nuclear physics and thermonuclear reactors - the future sources of energy. Magnetic and electric properties of superconductors are highly non-linear, what causes the need to apply numerical simulations to analyse them.

The main goal of this thesis is the analysis of operation of a superconducting bus-bar. The analysed bus-bar is the part of a cryogenic by-pass line for SIS100 accelerator constructed under FAIR project at GSI, Darmstadt. It is the part of Polish in-kind contribution to the project. The line is designed on Faculty of Mechanical and Power Engineering at Wrocław University of Technology. It contains four pairs of superconducting cables supplying dipole and quadrupole magnets with electric current. In thesis thermal and electromagnetic aspects of operation are considered. The main analysing tool are numerical simulations. Obtained results are analysed and, if possible, validated versus numerical measurements and analytical calculations.

It is checked how the simplifications of complex structure of a nuclotron cable affect the calculated values of electric parameters of the line. The analysis shows that the values of electric capacitance and inductance do not exceed expected limits and high quality of electric current supplied to the accelerator is ensured. To obtain sufficiently high reliability of the results of thermal analysis the model considering individual strands should be applied. Obtained results suggest that the operation of the bus-bar is safe in terms of quench and the operational parameters are far enough from conditions causing violent transition.

The additional goal of work is the analysis of operation of superconducting magnetic screens used to shape the magnetic field. Several numerical models with different levels of complexity are created. The first is the model of closed superconducting magnetic shield analysed with own numerical code *SuShi*. Then the open magnetic screen is analysed using commercial numerical modelling software Comsol. Obtained results march both experimental measurements and analytical calculations. After that the analysis of the bus-bar itself is performed. The initial model of nuclotron cable is created to analyse two methods of modelling of the superconductor. Obtained data is used to create electromagnetic model of the entire line and to calculate its electrical parameters. Then coupled thermal-electromagnetic model of the nuclotron cable is created to calculated heat generation and leaks.

In the initial chapters of the thesis the theoretical basics of superconductivity are presented. Described are physical mechanisms leading to the formation of superconducting state, its properties,

critical parameters and division of superconductors. Some applications of superconductors are presented. The main challenges of numerical modelling of superconductors are listed.

The first and simplest superconducting element which is analysed is a closed magnetic screen. This device is used to attenuate magnetic field at some are or to block its propagations (magnetic traps). Due to the application of the bulk superconductor almost entire magnetic field can be stopped. At the analysed screen the additional layer made of a superconducting tape is added leading to improved shielding of low frequency magnetic fields. This is the first simultaneous application of a bulk and a tape superconductor for magnetic shielding.

Numerical model of a multilayer screen was created yielding the results close to experimental. The geometry of such screen is simple and it is axially symmetrical. It is possible to analytically calculate the operational parameters of such device using Kim-Anderson's model. Again, numerical calculations were close to analytical results.

During the experimental measurements performed at Institute of Low Temperature and Structure Research of Polish Academy of Sciences in Wrocław the additional shielding effect appearing above certain threshold frequency was observed. In the thesis the analysis of this effect is presented i electrical parameters of the screen used to find the threshold frequency are calculated. The method of numerical calculation of inductance of the analysed screen is presented.

Then the analysis of an open magnetic screen is performed. The screen is going to be applied at electron cooling system of accelerator NICA constructed at Joint Institute for Nuclear Research in Dubna, Russia. The system is used to increase the quality of the accelerated particle by reducing its area and energy spread. It is done by electric interaction between the accelerated particles and an easily controlled electron beam. This process is the most efficient in highly homogeneous magnetic fields.

This screen has more complex geometry. Formation of highly homogeneous magnetic field is possible by the application of open magnetic screen made of superconducting tapes folded around common carcass surround the interaction region. Now there is no axial symmetry. Two separate models are created to calculate two components of a magnetic field. The first model applies H-formulation to analyse single, unfolded tape in 2D. With this model radial component of the field is calculated. Full distribution of shielding currents and magnetic field in a single tape is obtained.

In the case of the second model the new method to calculate equivalent shielding current in such geometry is presented. Based on it axial component of magnetic field and its distribution is calculated. Both experimental measurements and numerical model show significant improvement of the homogeneity of the field after the application of the screen. Numerical model is able to predict the behaviour of the screen in magnetic fields of different strength and shape.

After obtaining the data on the application of commercial software in numerical analysis of superconductors the main goal of work is achieved - thermal and electromagnetic analysis of superconducting bus-bars for SIS100 accelerator is performed. To analyse the distribution of magnetic shielding around the superconductor the numerical model of nuclotron cable is created. Two modelling methods are considered - with superconductor modelled as separate strands and as a solid superconducting region. The model with separate strand requires much larger number of numerical nodes and leads to the significant increase of computation time. It is assumed that the temperature of the cable is constant. Empirical dependence of critical current density on magnetic field is implemented.

The analysis of results has shown that to model the distribution of the magnetic field it is sufficient to apply faster model with a solid superconducting region. Magnetic field differs only in the region of the strands. Further from the axis of the cable it is almost identical. Because of that any discrepancies will not affect significantly the values of electric parameters depending on magnetic and electric fields generated by the cable at some distance. However, thermal model should employ the method with separate strands to use the exact value of current in a single strand. Large differences of electric current density are observed between models, leading to large deviations in the size of heat generation.

Electric parameters of superconducting line are calculated numerically. Electric capacitance of the line is calculated for three cases defined by placing electric potential at different location. Capacitance between two nuclotron cables, pair of cables and a shell, a single cable and a shell is analysed. Three methods are used basing on energy, electric displacement field and stored electric charge. Values obtained with each method are very close to each other and analytical.

Self-inductance and mutual inductance of the line are calculated. To find self-inductance of the straight fragment of the line the 2D-model is used, employing energy method and linking flux method. In dilatation region the 3D-model and energy method are used. To calculate the mutual inductance of straight fragments the 2D-model with linking flux and induced voltage methods is used. Mutual inductance in dilatation region is found using the 3D-model and induce voltage method.

Based on obtained values of inductance cross-talk currents are calculated. Inductances of the accelerator magnets is considered. Obtained values are much lower than the assumed limit. It ensures high quality of magnetic field generated by the accelerator magnets.

Eddy currents induced in the shell of the bus-bar are also calculated. Obtained results are analysed in the context of both quality of supplied current and generation of heat in superconductor and conducting elements of the line. The strength of these currents is very small and causes insignificant changes of currents in superconductor and negligible heat generation in the shell.

For thermal analysis two models are created. The first calculates the amount of heat transferred to the superconducting cable. The entire geometry of the cross-section of the cryogenic line in the region without spacers is recreated. The parameters of heat transfer to the coolant and from the surroundings are calculated. The main regime of heat transfer between the elements of the line is thermal radiation. Static heat leaks are calculated this way. The obtained value of heat transfer is passed to the model of the superconducting cable.

Power losses in nuclotron versus applied current are calculated. Coupled thermal-electromagnetic model is created. The dependence of critical current density on magnetic field and temperature is applied. A single cross-section of the nuclotron cable is modelled. Obtained results allow to asses the risk of quench during the normal operation of the cable. It is shown that the size of losses in the superconductor do not depend directly on the applied current. The calculated amount of generated heat is relatively small and the risk of damage to the superconductor is low.

All goals of the thesis are achieved and the points are proved to be true. It is shown that the application of the analysed cryogenic is safe and will ensure proper quality of the operation of the accelerator. During the realisation of additional goals several interesting effects are analysed. The multitude of possible applications of superconductors in high energy is presented, as well as the usefulness of numerical simulations in their analysis.