Study on Reduction of AC Loss in Tri-Axial Cable Using Bi-2223 Superconductor

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論文内容要旨,

This thesis is presented for realization of HTS cable for future use in electricity distribution and transmission. In metropolitan, the infrastructure is complex and crowded; and power capacity increment is required depending on energy demand. HTS cable is an opportunity to retrofit existing copper cable ducts, therefore maintains installment ease and cost reduction for future use. Due to that smaller HTS cable size more easily fits the existing ducts, tri-axial cable is a good component to the other HTS cable types for practical use in limited spaces: in addition it is cheaper, environmental friendly and leak heats are at low level by which refrigeration becomes cheaper. On the contrary, tri-axial HTS cable has two main realization difficulties. One of them is unbalanced three phase property; which makes tri-axial cable deteriorate the power quality of the utility service. Second of them is the out-of-phase property which make transport losses difficult to estimate. Solution of those problems is important for tri-axial cable application. Therefore, this thesis is mainly is about solving unbalance and AC loss problems of the tri-axial HTS cables, as follows.

In Chapter 2 of this thesis, we challenged the inherent imbalanced currents of the tri-axial cable due to its harms on power stability, therefore we expressed the unbalanced behavior with examples. For solving this problem, first we expressed the balancing equations in a tri-axial HTS cable and then showed that those equalities are not enough for solution, since there are not enough parameters required for independent twist pitch solution. Due to that problem, we used a 2-segment layers for each phase of the tri-axial cable; which is a previously proposed solution method. By the help of 2-segment cable, the number of unknown twist pitch variables are doubled and thereby the equations became solvable. Hence, we

obtained both balanced and homogenous current distribution equations neatly, designed for the proposed 2 segment tri-axial cable. The equations are also arranged for several layers per phase tri-axial cable and thereby general balancing formulation of the tri-axial HTS cable is given. As a final outcome of these equations, we expressed the clear solutions of a one layer and two layers per phase cable.

As a second stage, we showed the balanced theory is applicable in real tri-axial HTS cable applications. First, we designed a tri-axial cable with specific radii, and then simulated the design. We analytically solved all twist pitches and found out the simplest tri-axial cable which require minimum manufacturing effort. According to the simulation results, the balanced cable is possible to be used in 3 phase applications. Next, we manufactured all phase layers and checked the self inductances of individual layers before the 3-phase test and noted the measurement results. During the tests, cable is immersed in to LN2 bath in order to maintain application ease and observation simplicity; where manufactured cable is 1 m in length. Finally, we realized the simulation by manufacturing 1 m length tri-axial cable. Here we note that, since the design requires minimum effort, we only produced one joints between segments and totally produced 4 layers. The completed manufacture is tested under 3 phase current supply, and three phase balanced voltages on the cable are measured. According to the results, the findings match with the simulation results, thereby the tested cable satisfies 3-phase balanced operation. Therefore the balanced tri-axial cable is applicable in real HTS cable applications.

Additionally, we considered the tri-axial cable for investigation of optimum voltage drop. We used segment lengths as variable parameters and found out minimum voltage drop results for different segment length configurations. We analyzed the balanced three phase current distribution for 1 layer per phase tri-axial cable and additionally we analyzed the homogenous current distribution for 2 layer per phase tri-axial cable. We purposed to get the optimum fabrication parameters for obtaining minimum voltage drop for various segment length lengths and reported the results by individual graphs.

In Chapter 3, we aimed derivation of out-of-phase AC loss formulation in HTS slabs, since we require hysteresis loss formula designed for the tri-axial cable. For this aim, first, we investigated the magnetic field penetration process inside the superconductor slab. Therefore, we showed various cases of field penetration process changing according to the outer surface field magnitude and direction. The basic calculation of AC loss formula is presented. Since this formula depend on the assumed model named as Critical State Model, we expressed this issue in detail; where the magnetic field always penetrates into the tape from its surface with the critical current according to the model.

Secondly, the AC loss formula for in-phase magnetic field is presented. The formula is solved based on same phase fields that are smaller than penetration field of the superconductor tape. The calculated field loss is used through out the thesis where total field is smaller than the penetration field. In practical applications, a superconductor carries transport current in alternating magnetic field and the total loss is the sum of two loss kinds, therefore the hysteresis loss formula for self magnetic field and transport current loss is separately defined. Both losses depend on the current amplitude and magnetic field amplitude, therefore the total AC loss increases in case they are increased.

Additionally, different amplitude in-phase fields are investigated. The field penetration is shown by a figure and AC loss formula derivation is made. This penetration process is more complex rather than the small amplitude field penetration, in case applied field is larger than the penetration field of the tape. The magnitude of the applied field is enough for formulation.

Finally, we derived the out-of-phase AC loss of the superconductor tapes. In tri-axial cables, the external field does not synchronize with the transport current, therefore so called out of phase external field is applied on the tapes. Since produced field of a tri-axial cable is in parallel with the wide surface of the tape, slab model is applicable for the formulation. The behavior of this kind of field in the tape is complicated; thereby we made the loss mechanism clear, and then derive the formula of the consequent hysteresis loss. We investigated the penetration process for small amplitude fields and large amplitude fields, separately. For both conditions, we obtained the two surface fields and sum up the results. In case of large amplitude fields, two surface fields reach the center of the slab and interacts each other, therefore field penetration point behaves in a complicated way. Due to that reason, interaction time and phase difference between two surface fields are counterparts of the AC loss formula. Using the counterparts, we finally expressed the derived AC loss formula which is used through out the thesis.

In Chapter 4, we derived AC loss formula of the balanced tri-axial HTS cable. Since AC loss of the tri-axial HTS cable is functions of transport current and out-of-phase external field, we calculated all fields produced within the concentrically wounded tri-axial phase layers. Here, the azimuthal fields are inverse proportional to radii, therefore we need to determine the most inner radii of the cable, and the air gap between each layers. On the other hand, the axial fields are inverse proportional to the twist pitches. From the equations, it is shown that shorter twist pitches will lead to higher losses. Basically, we expressed all magnetic field equations for the azimuthal field which penetrates into the HTS layer from outer surface, and axial field which penetrates into the HTS layer from inner surface. It is shown that all phase layers experience different phase magnetic fields that are parallel to wide surfaces, due to that the out-of-phase AC loss equation derived in Chapter 3 will be used for total loss calculation of the tri-axial HTS cable.

As mentioned, the tri-axial cable tapes experience parallel component of magnetic field on the wide faces of HTS tapes, therefore the fields on tapes generate magnetization losses. Hence we calculated produced net fields of a tri-axial cable depending on the net phase angles of applied fields. In the second stage we considered balanced current distribution is satisfied within the tri-axial cable. We solved net resultant fields for individual phase layers and the final formula is expressed for individual phase layers; separately identified by net field magnitudes and net resultant field angles.

Finally, readily deriving the AC loss formula and magnetic field distribution within the tri-axial HTS cable, we applied the formulations on specific examples. Here we investigated the effect of main construction parameters on AC loss. AC loss is graphed as a function of all cable parameters, namely segment length ratio, segment twist pitch ratio, radius, air gap and twist pitch direction. AC loss calculations are separately done for the azimuthal and axial fields. The total loss is the sum of the two loss types, therefore we separately calculated the fields and losses on different layers. We discussed the consequent results at the end of each investigation. According to overall results, the axial field loss is an important counterpart of total AC loss; therefore needs special attention.

In Chapter 5, we studied reduction of AC loss in tri-axial HTS cable. Additionally, we compared the tri-axial cable loss with that of widely used co-axial cables. Here, first we showed that AC loss in tri-axial cable design is mainly a matter of twist pitch lengthening. For this aim, we used radii as a comparison parameter versus radii and plotted AC loss as a function of the parameters. According to the results, the axial field losses become lower than azimuthal field losses if twist pitch length become longer than the corresponding layer circumference, generally. Otherwise, the axial field loss shares the dominant role in total AC loss of the cable; therefore twist pitch lengthening is important in lowering tri-axial HTS cable loss. Here, we noted that azimuthal field AC loss is mostly unchangeable and considered constant unless voltage class and transport current is changed. Thereby, continuing parts of this section are devoted to decrease axial field loss of the tri-axial cable.

In order to investigate axial field loss reduction, we induced all twist pitches as a function of construction parameters. As an outcome of this research, we found out that segment lengths and segment pitch ratios are independent of the radii parameters. The solutions are expressed by f and g functions separately; namely f functions are depending on segment length and segment pitch ratios; on the other hand g functions are depending on radii. The two functions do not have any relations between each other and all segment twist pitches are products of the two functions, hence twist pitches can directly be controlled by f function. We expressed that, controlling g function and thereby AC loss is not possible in tri-axial HTS cables.

Hence, depending on f function, we studied the longer twist pitches in terms of AC loss reduction and obtained f function components. Finally we extended our study for different size of cables depending on determined f function value. For this aim, we obtained the AC loss of those different size cables and plotted all results as a function of the phase-c pitches which corresponds individual twist pitch sets.

Depending on the twist pitch set and corresponding AC loss obtained, we compared the results with that of the co-axial cable depending on the same comparison criteria. According to the results, the AC loss of the tri-axial cable is lower than the co-axial cable, for the same duct size. The comparison results are shown within individual graphics, and we showed that the difference between two cables is due to the azimuthal field loss. The reasons of the azimuthal field difference are investigated and results are expressed concretely. According to the results, the main reason for the big difference between the azimuthal field losses of the two cables stem from the shield layer losses of the co-axial cable.

論文審査結果の要旨

高温超電導体は，液体窒素温度において超電導状態となることから電力応用機器に適用することで，環境・エネルギー問題の革新的な解決策の一つとして社会貢献できると考えられている。特に高温超電導ケーブルは，従来の電力ケーブルと比べて低損失かつコンパクトになることから，CO_2削減・省エネルギー・省スペースなどの面で大いに期待されている。しかしながら，高温超電導体は低温で使用するため僅かな損失でも常温での動力に換算すると大きな損失となるために，熱侵入の低減や，交流通電時に発生する交流損失の低減が電力ケーブルを実現する上で重要な課題となっている。本論文は，高温超電導ケーブルのコンパクト化と低交流損失化の実現を目的として，超電導ケーブルにおける諸課題を明確にし，三相同一軸ケーブルの平衡電流分布構成の新規提案，およびその実験的検証，ケーブルの交流損失の解析方法の導出，ケーブルの交流損失低減化の設計指針に関する研究を行ったもので，全編6章からなる。

第1章は緒言であり，本研究の背景と目的を述べている。

第2章では，Bi-2223 超電導線材を用いた超電導ケーブルの三相平衡電流分布に関する課題を明確にして，その対策について論じている。三相同一軸ケーブルは種々のケーブル構造の中で超電導線材の量を最も少なくコンパクトにできる構造であるが，等しいピッチで線材を巻きつけた構成では，各相の電流分布が不平衡状態となり，不平衡電流成分が中性線に流れて大きな損失や電圧の不均一をひきおこす。三相平衡電流分布はケーブルを2分割してピッチを調整することにより理論的に実現できることを初めて証明し，長さ1mの超電導ケーブルを試作して実証した。これは超電導ケーブルを実用化する上で極めて有用な成果である。

第3章では，三相同一軸超電導ケーブルの交流損失解析の課題を明確にしている。通電電流と外部磁界の位相が異なるため，従来の交流損失計算では取り扱えないことが分かった。位相が異なる場合の交流損失解析方法を新しく導出し，定式化を行った。これは高温超電導ケーブルの低交流損失化を検討する上で重要な成果である。

第4章では，コンパクト性を有する三相同一軸ケーブルの交流損失解析をするために，各相電流と外部磁界の位相や大きさの関係を明らかにし，三相平衡電流分布を維持したケーブル構成で，ケーブル半径や，ケーブルの分割比，電気絶縁層厚さなどのケーブルパラメータと交流損失の関係を明確に示した。これは三相平衡である三相同一軸ケーブルの設計に有効である。

第5章では，第2章から第4章までに得られた研究成果に基づいて，交流損失を低減できる三相同一軸ケーブルのパラメータを明らかにし，線材を巻きつけるピッチが最も重要であることを証明した。さらに，単相3本構造の三相超電導ケーブルの交流損失と比較して，新しく提案した三相同一軸ケーブルの交流損失が大幅に減少できることを理論的に証明した。これらはコンパクト性を有する低交流損失型三相同一軸ケーブルの最適設計指針として実用上高く評価される。

第6章は結言である。

以上要するに本論文は，Bi-2223 高温超電導線を用いた三相同一軸ケーブルを実現するために，三相平衡電流分布の成立理論の提案とその実証，また，電流と磁界の位相が異なる場合の交流損失解析の導出，およびそれを三相同一軸ケーブルに適用して交流損失低減技術を確立したもので，超電導応用分野の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。