（ 続紙 1 ）

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論文題目	Study on Impacts of Geomagnetic Disturbances on Power Systems （地磁気擾乱による電力系統への影響に関する研究）		

This thesis focuses on the geomagnetic disturbances (GMDs), including sudden commencements (SCs), main phase of magnetic storms and bay disturbances, that induce large-amplitude geoelectric fields. The induced electric field variations produce geomagnetically induced currents (GICs) in power systems, which may cause harmful impacts to the power grids. Sudden commencement events due to solar wind dynamic pressure pulses are further investigated by magnetohydrodynamic (MHD) simulations, which explains why power systems in high-latitude regions are more susceptible to GIC harm due to GMDs associated with field-aligned current (FAC) systems.

The first chapter provides a general introduction to the background of this thesis. Basic knowledges of space physics involved in this thesis, including solar wind, space weather, Earth's magnetosphere, current systems in the magnetosphere and the ionosphere and GMDs and GICs, are described in detail. The effects of geomagnetic disturbances on power systems are also introduced from the facets of sources, mechanisms and results.

The second chapter shows the analysis of geomagnetic and geoelectric field data measured at Kakioka Observatory in Japan to acquire a quantitative relationship between them for different types of geomagnetic disturbance (GMD) events, whose purpose is to establish a fast way of calculating the geomagnetically induced currents (GICs) generated correspondingly in Japanese power grids. First, regression equations for the relation between the geomagnetically induced electric field and the corresponding geomagnetic field variations at Kakioka Observatory are derived for 213 sudden commencements (SCs), 36 magnetic storms and 325 bay disturbances. Then the GICs flowing in three power substations around the observatory are calculated by using the empirical model of the previous study for a certain power network (topology and parameters) based on the estimated GIEs. The underlying maximum GICs for extreme GMD events are also predicted through the generalized extreme value distribution (GEVD) method, which is useful for evaluating the possible GIC risks against extreme GMD events and forecasting the maximum GICs in a real-time manner.

The third chapter deals with the geomagnetic disturbances that caused a widespread blackout in Canada in March 1989 due to a GIC. In Canada, the magnetic disturbances were observed to be positive (northward) at high-latitude regions, whereas negative (southward) at low latitudes. The tendency of the geomagnetic fluctuations is reasonably reproduced by the magnetohydrodynamic (MHD) simulations under a condition of solar wind pressure pulse. The simulation results show that when an interplanetary shock wave arrives, vortices of strong electric current start flowing in the ionosphere, and move to the nightside. This current significantly changes the geomagnetic field, which in turn induces large-amplitude electric currents flowing in the power grids, and could result in the widespread blackout in Canada in March 1989. In generating large GICs, the important role of the current vortices in the ionosphere is pointed out. It is shown that the shock-associated ionospheric current is harmful to power systems in high-latitude regions not only on the dayside, but also on the nightside.

The fourth chapter describes the origin of the current vortices shown in the third chapter. It is well known that when the interplanetary shock arrives, field-aligned currents (FACs) are generated in the magnetosphere, resulting in the intensification of the ionospheric currents and the magnetic disturbances. However, the generation mechanism of the shock-associated FACs is not fully understood. By using global MHD simulations, entire physical processes from the interplanetary shock to the generation of the shock-associated FACs are proposed. When the shock arrives, it compresses the magnetosphere, resulting in two types of magnetic disturbances subsequently observed. The first one is called a preliminary impulse (PI), and the second one is called a main impulse (MI). The reason why the polarity of the FACs during the preliminary impulse (PI) is different from that during the main impulse (MI) is also explained in terms of dynamical processes. This study provides a deep understanding of the geomagnetic response in high-latitude regions to solar wind dynamic pressure jumps.

The fifth chapter is about conclusions and prospects. The chapter summarizes the results obtained in the thesis and mentions putting forward directions of future studies.

（続紙 ２ ）

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（論文審査の結果の要旨）

本論文は、地磁気と地電場の観測値及びシミュレーションを用いて得られた電力系統に対する地磁気擾乱の影響に関する知見をまとめたものである。主な成果は以下の通りである。

1. 柿岡地磁気観測所で測定された地電場を地磁気誘導電流(GIC)のプロキシとし、日本における主な地磁気変動のタイプである急始（SC)、磁気嵐、湾型変化の 3 種について、地磁気変動と地電場の関係を明らかにした。地電場の最大振幅は SC の時に最も大きく、磁気嵐と湾型変化がそれに続くことや、地磁気変動の最大振幅と地電場の最大振幅には線形関係があることを示し、その比例定数を導出した。一般極値分布（GEVD）法による極端値解析を行い、回帰周期 10 年、100 年間の地電場の最大振幅を求めた。

2. 電磁流体シミュレーションを用い、1989 年 3 月にカナダで GIC を原因とする広域停電が発生した時の地磁気変動を概ね再現できることを示した。惑星間空間衝撃波が到来して SC が発生し、電離圏では初期インパルスに続いて主インパルスと呼ばれる強い電流が流れて地磁気を大きく乱し、カナダでの広域停電を引き起こした可能性を示した。電力系統への影響が高い地域を示すため、太陽風パラメータごとに地磁気変動の全球マップを作成した。GIC に対するハザードマップとしての活用が期待される。

3. 電磁流体シミュレーションを用い、SC に伴って増大する沿磁力線電流(FAC)の原因と、その生成領域を特定した。惑星間空間衝撃波が磁気圏を圧縮し、磁気圏で生成された沿磁力線電流が電離圏と接続して電離圏電流を強め、地上の磁場を乱すまでの一連の物理過程の詳細を明らかにした。沿磁力線電流の極性が初期インパルスと主インパルスで異なる理由も磁気圏内の動力学の観点で示した。

日本における地電場変動の特性および、SC に伴って高緯度地域を流れる電離圏電流とその原因となる沿磁力線電流の生成過程を明らかにした。地磁気変動と地電場の関係式を導き、地磁気変動の全球マップも提示した。これらは、電力設備保護の観点から重要な知見であり、変圧器の設計や電力会社における系統運用への活用が期待され、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和 6 年 8 月 19 日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。

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