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Review of mitigation technologies for terrestrial power grids against space weather effects

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ABSTRACT

This paper discusses the earth-based effects of solar weather and presents a review of mitigation and protection techniques for the terrestrial power grid infrastructure. Solar events such as Coronal Mass Ejections (CMEs), solar flares and associated recombination events are one of the driving factors in space weather and the solar wind intensity. Even though it is located at such a great distance from our nearest star, the Earth and its associated satellites are still directly affected by variances in these space weather phenomena. On the surface of the planet, nowhere is this more immediate and important than with the terrestrial power grid, which is responsible for delivering electrical power to much of the planets population. Large-scale variations in solar activity can result in potentially devastating effects on the terrestrial power grid and the associated infrastructure.

A team project was undertaken at the International Space University (ISU) Space Studies Program (SSP) 2013 to categorize and mitigate the risks involved in such a solar event. As part of this research, which included risk assessment for satellite, spacecraft and terrestrial resources, this paper presents a review of the terrestrial power grid and its inherent susceptibility to such phenomena. Mitigation schemes, techniques and approaches ranging from adaption of the existing power grid to alternative systems are considered in this paper, which allow for continued electrical power delivery and transmission, even in the face of such detrimental space weather effects.

Introduction

Opening

“Space Weather Destroys Stuff” – [1]. A bold and undeniably truthful statement from Dr. Pete Worden and the T.P SolarMAX team of the 2013 Space Studies Program at the International Space University [2]. In the past 100 years, the Earth and associated (highly susceptible) technological advances of the last century have escaped the attention and associated destructive side-effects of any major solar event. The cause and effect of such solar storms, space weather and solar activity are still an area of ongoing research within the scientific community, with new discoveries being made and mysteries solved even today [3].

In this paper, the term “Solar Events” is used to encompass any solar-related phenomenon with wide-reaching effects on other bodies in the solar system. Coronal Mass Ejections (CMEs), solar flares, magnetic recombination on the surface of the sun and other associated phenomena are all included under this heading [4]. In the Earths recent history, the largest coronal mass ejection and associated phenomena recorded occurred in 1859, and is nowadays referred to within the scientific community as the “Carrington Event” [5]. Were it to happen today, an event of this magnitude would have a disastrous impact on humanity, both on and off our planet. In 1859, aside from the spectacularly visual aurora associated with the phenomenon, the Carrington Event, while it was of a magnitude and scale heretofore unseen, the solar activity went largely unnoticed. Telegraph operations were one obvious exception, with the space weather events sufficient to interfere with transmissions and, in extreme cases, power the telegraph lines unaided for hours at a time.

Nowadays, a space weather event on this scale would have wide-reaching and, in many cases, disastrous effects on Earths technology, infrastructure and assets. With all of the technological and electrical improvements in the past 150 years, our modern

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planet and its people are largely dependant on technology, electronics and electrical power for many of the services, conveniences and comforts taken for granted in the modern world: light, heating, communications, transport, healthcare, safety and security foremost among these. Solar activity comparable to that witnessed in 1859 would see the Earth suffering major setbacks, losses and potential regression due to our singular state of unpreparedness with respect to these space weather incidents. Nowhere would this impact be more widely felt than in the modern-day terrestrial power grid, which supplies electrical power to the majority of cities, communities and homes across the globe.

Terrestrial power grids

During geomagnetic storms, electric currents in the atmosphere and the associated magnetic field undergo large variations due to fluctuations in the solar wind intensity. These variations cause geomagnetically induced currents (GICs) in terrestrial conductors, such as power lines and buried pipelines. The terrestrial power grid, or electric-power transmission grid, refers to the bulk transfer of electrical energy, from generating power plants to electrical substations located near distribution centers. The associated transmission network is the interconnected mesh of these transmission lines, used to distribute the electrical power within a country or geographical region. Given a sufficiently active solar event, the currents induced in terrestrial power grids and transformers may be large enough to cause temporary or indeed permanent damage to the constituent elements of the power grid, resulting in temporary loss of power for large areas of the grid.

Historically, the transmission and distribution of electricity have been coordinated by the same company or institution. Starting in the 1990s, however, many countries have liberalised the regulation of the electricity market, which has meant that the electricity power generation business is now generally distinct from the power distribution and transmission lines sector (Fig. 1).

Most modern-day transmission lines use high-voltage three-phase alternating current (AC) for most transmission and industrial usage. One noteworthy exception to this is railway electrification systems, which still use single phase AC [6]. High-voltage direct-current (HVDC) technology is used for greater efficiency in very long distances (usually hundreds of kilometers)), or in submarine power cables [7]. HVDC links are also used to stabilize against control problems in large power distribution networks where sudden new loads or blackouts in one part of a network can otherwise result in synchronization problems and cascading failures.

Electricity is transmitted at such high voltages (110 kV or above) to reduce the energy lost in long-distance transmission by minimising the transmission current through an inversely proportional increase in transmission voltage. Power is typically transmitted through overhead power lines. Underground power transmission has a significantly higher cost and greater operational limitations, and so is only used in specific conditions, such as inner city power grids.

Transmission lines are therefore designed to transport electrical energy as efficiently as possible, while still taking into account economic factors, network safety and redundancy. The associated power grids use components such as circuit breakers, switches and transformers in addition to transmission lines and cables to realize their desired implementation. A power transmission grid is therefore a network of power stations used in conjunction with these transmission lines, power grids and substations to supply electricity to the end user.

The associated cost of electric power storage is high, therefore most power grids utilize the generated electricity immediately rather than store it for later use. As the typical electricity demand (load) is variable over days, regions and seasons, it is often more economically feasible for power companies to import any excess portion of the high-demand power requirements than to store or generate it locally. Because of the associated economic benefits of this load sharing between countries or regions, wide area transmission grids now span countries and even continents.

However, this reliance on concurrent power generation and wide-scale power distribution networks and transmission lines, with minimal provision for energy storage, proves dangerously shortsighted when geomagnetically induced currents and space weather effects are considered.

Geomagnetically induced currents

Geomagnetically induced currents (GICs) are a manifestation at ground level of space weather, and are known to affect the normal operation of long electrical conductor systems, such as the power grids or electrical transmission systems described in the preceding section. During geomagnetic storms, electric currents in the magnetosphere and ionosphere undergo large variations due to correspondingly large fluctuations in the solar wind intensity caused by these storms. This time-varying magnetic field, which is external to the Earth in the atmosphere, induces telluric currents (electric currents) in the conducting ground. These magnetospheric and ionospheric variations also manifest in the Earths magnetic field, creating a secondary (internal) magnetic field, inducing an electric field at the surface of the Earth associated with these time variations in the magnetic field (Fig. 2).

This surface electric field causes electrical currents (GICs), to flow in any conducting structure, such as a power or pipeline grid grounded in the Earth. This electric field, measured in V/km, acts as a voltage source across networks. GICs are often described as being quasi direct current (DC) in nature, although the variation

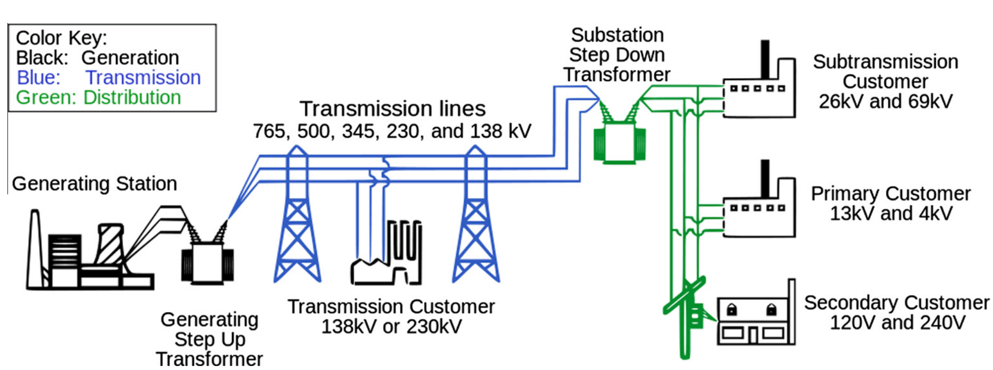

Fig. 1. Electrical power grid – image courtesy Wikipedia.