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Geo-magnetic Disturbances

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Geo-Magnetic Disturbances

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Introduction

A once-in-a-century solar storm event could induce a power surge into the electric transmission system plunging much of the United States into a blackout that may last several months or even a year or longer. The electric system for as much as one-third of the country could be immediately disrupted with an event equal to the 1921 "New York Railroad" event. However, many experts say that the automatic protections built in the U.S. electric grids would immediately operate on the initiation of a geo-magnetic disturbance (GMD), creating widespread blackouts, but very little damage to the system. In this case, the electric grid could be back in operation in a matter of days. Still the economic impact of a momentary outage is enormous.

Geomagnetic storms — a type of space weather that creates disturbances that affect the planet's magnetic field —have the potential to cause significant damage across the globe with a single event. Severe geomagnetic storms can disrupt the operation of electric power transmission systems and critical infrastructures relying on space-based assets. A geomagnetic storm that degrades the electric power grid would affect not only the energy sector but the transportation, communications, banking, and finance sectors, as well as government services and emergency response capabilities.

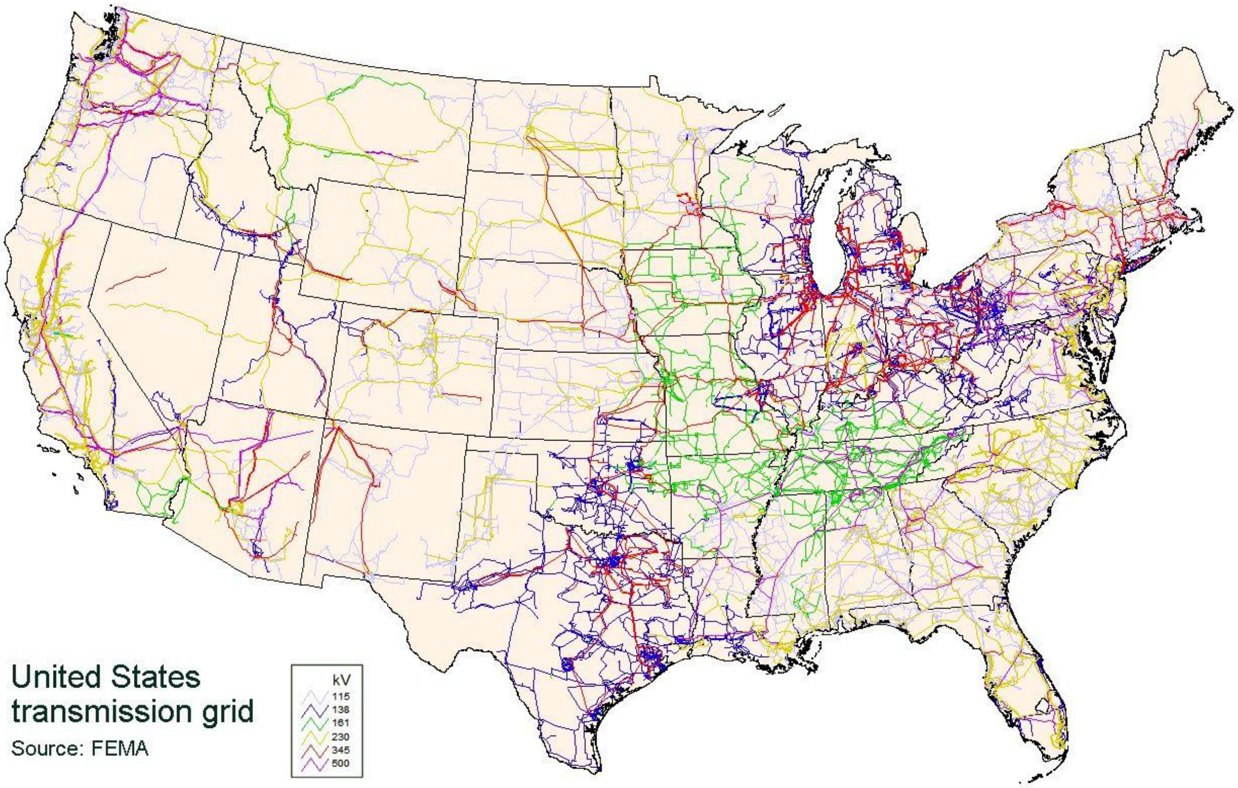
Issues with geo-magnetically induced currents (GIC) have been known since the mid-19th century when it was noted that electrical telegraph systems could sometimes run without power during geomagnetic storms, described at the time as operating on the "celestial battery", while at other times they were completely inoperative.

The North American bulk electric power system is perhaps the most critical infrastructure on the continent, for its continued reliable operation supports several other critical infrastructures, including water supply, telecommunications, food and fuel production and distribution, and others. It underpins our government, economy, and society in crucial ways. The U.S. National Academy of Engineering ranked electrification as the greatest engineering achievement of the 20th century, ahead of automobiles, telecommunications, computers, and even healthcare in terms of it positive impact on quality of life.

The extra high voltage (EHV) portion of the grid (345-765 kV) typically experiences the highest GIC flow levels, in part because these lines and connected transformers also have lower resistance per mile than the lower voltage underlying systems and the ground impedance. The loss of these key assets due to large GIC flows on the high voltage system can rapidly widen into geographically widespread disturbances on the power grid.

Power systems may be more vulnerable to the effects of a severe geo-magnetic storm than a few decades ago. Since the 1950s, the number of miles of high-voltage transmission lines has increased by about a factor of ten. Hence, the number of assets that provide a conductive path for GICs has increased dramatically over the last five solar cycles. During the same period, transmission line and transformer designs have increased in voltage from 100-200 kV to 345-765 kV, which has lowered their resistance by a factor of ten and further increased their susceptibility to GMDs. And the conducting paths are lengthening as transmission lines become interconnected (e.g., across national borders).

In the last two decades, construction of new transmission lines has slowed forcing some utilities to operate the bulk power system closer to operating limits more often. This increases the vulnerability to overloads caused by GMDs because the equipment may be operating closer to its nameplate thermal rating when the GIC initiates additional heating. The North American power grid is highly complex; it is comprised of over 200,000 miles of transmission lines, thousands of generating plants, and millions of digital controls (See Figure 1.) Yet, industry has demonstrated a long track record of reliable, secure delivery of power, however, without adequate steps to mitigate their effects, geo-magnetic disturbances (GMDs), may pose a risk to reliability.



Source: FEMA

Figure 1

GMDs start with the sun. Solar coronal holes and coronal mass ejections (CMEs) are the two main categories of solar activity that drive solar magnetic disturbances on the Earth. CMEs involve the ejection of a large mass of charged solar energetic particles that escape from the sun’s halo (corona), in a matter of days, or sometimes just a few hours (see Figure 2.)

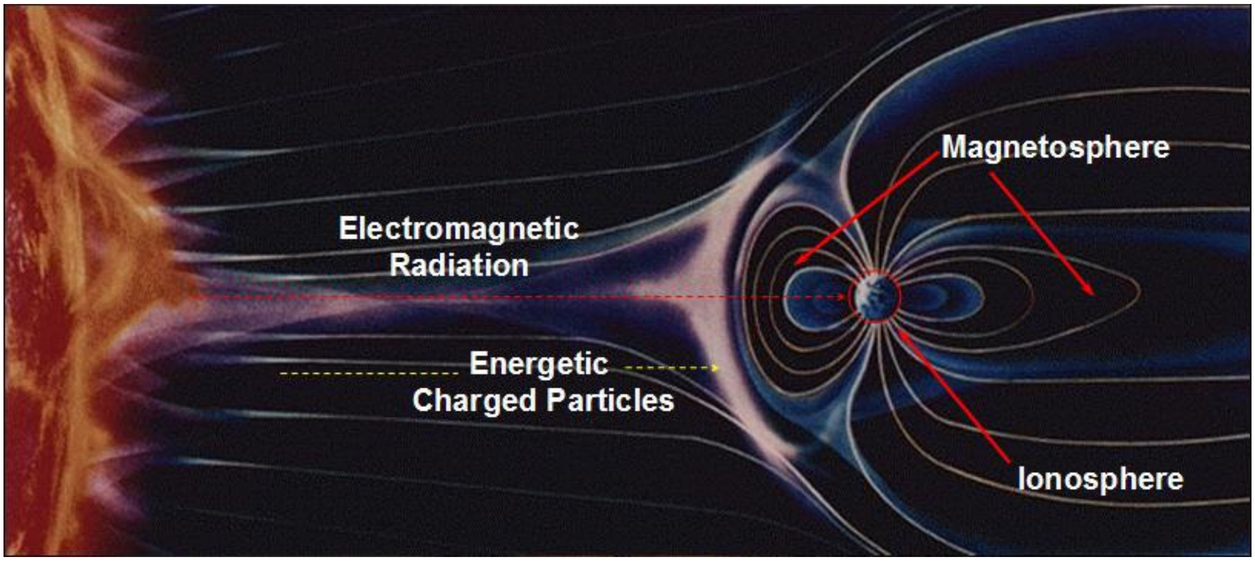


Figure 2 Source: National Weather Service

Solar storms, which emanate from the sun as coronal mass ejections (CMEs), can produce an impulsive disturbance to the Earth's geo-magnetic field over wide geographic regions.

A severe geomagnetic storm is defined as any event with a disturbance storm time of less than -500 nanoTeslas. No recorded geomagnetic storm since 1932 has exceeded -760 nT.

The storms are global phenomena; a single severe storm can adversely impact systems on multiple continents. The disturbance in the Earth's geo-magnetic field can cause geo-magnetically induced currents (GICs) in the ground and electrical network. Once they are introduced into the bulk power system's transmission and generation facilities, these ground-induced currents can saturate and may damage some equipment, which can be difficult to immediately replace, such as high voltage transformers, which require long lead times to construct.

These quasi-DC currents can enter and exit the power system at transformer grounds disrupting the normal operation of the power system and can, in some cases, damage equipment. Because of their proximity to the Earth's magnetic north pole, higher latitudes typically experience greater effects of GMDs. However, a severe storm can affect equipment and systems even at lower latitudes.

Over the past decade, natural hazards have caused catastrophic consequences across the globe. Tsunamis, hurricanes, flooding, earthquakes, and volcanic eruptions have led to hundreds of thousands of fatalities and billions of dollars in economic costs. Significant geomagnetic storms happen less frequently, but have the potential to cause considerable damage across the globe with a single event. In the past, geomagnetic storms have disrupted space-based assets as well as terrestrial assets such as electric power transmission networks. Extra-high-voltage transformers and transmission lines may be particularly vulnerable to geo-magnetically induced currents caused by the disturbance of Earth's geomagnetic field. The simultaneous loss of large numbers of these assets could cause a voltage collapse and lead to cascading power outages, resulting in significant economic costs to the Nation. An extreme geomagnetic storm is a low-probability, high-consequence event that could pose a systemic risk to the Nation.

Historical Geomagnetic Events

Great solar storms occur approximately once per decade. Table 1 lists the major solar storms over the past 150 years. The largest solar storm ever recorded occurred in September, 1859 and is known as the "Carrington Event".

Table 1

Major Solar Storms

Event	Year	Strength
Carrington Event	1859	-1,750nT
New York Railroad Event	1921	-1,060nT
Quebec Event	1989	-589nT
Bastille Day Event	2000	-301nT
Halloween Event	2003	-383nT

The events shown in Table 1 are discussed in more detail below.

Carrington Event – 1859

On September 1 – 2, 1859, the largest recorded geomagnetic storm occurred. From August 28 until September 2, 1859, numerous sunspots and solar flares were observed on the Sun, the largest flare occurring on September 1st. This is referred to as the 1859 solar super storm or the Carrington Event. It can be assumed that a massive Coronal mass ejection (CME), associated with the flare, was launched from the Sun and reached the Earth within eighteen hours — a trip that normally takes three to four days. It is estimated that the *Dst* would have been approximately -1,750nT. Scientists reached this conclusion by analyzing anomalous nitrate concentrations in polar ice core samples and estimating the fluency of protons, which are an indicator of the amount of solar energetic particles that reach the Earth. This event was named after British amateur astronomer Richard Carrington, who observed a white flare light the day before the onset of the storm – an observation independently confirmed in London, England.

These were manifestations of two intense magnetic storms that occurred, driving magnetometer readings off their scale and disrupting telegraph communications worldwide. Unfortunately none of the observations enable a direct estimation of the geo-electric field. More specifically, large GICs were observed via their dramatic effects on telegraph equipment but the actual electric current amplitudes or geo-magnetically induced voltages were not recorded anywhere at the time.

Dst is an abbreviation for the Disturbance Storm Time index that measures the strength of the magnetic storm by averaging the horizontal components of the geomagnetic field.

Aurorae were seen as far south as Hawaii, Mexico, Cuba, and Italy — phenomena that are usually only seen near the poles. Ice cores show evidence that events of similar intensity recur at an average rate of approximately once per 500 years. Since 1859, less severe storms have occurred in 1921 and 1960, when widespread radio disruption was reported.

The New York Railroad Event - 1921

The highest magnitude GMD of the 20th century occurred on May 14-15, 1921. The storm disabled all telegraph service from the Atlantic coast to the Mississippi River and in major portions of the western U.S. The New York Times reported that submarine cables would need to be brought to the surface for repairs. No GMD of this severity has tested the power grid since then – not even the 1989 storm. The 1921 storm may have been ten times stronger than the 1989 storm that collapsed the Hydro Québec system. However, sophisticated monitoring equipment, widely deployed today, was not available at the time of the storm, making exact replication of the storm signal impossible. The minimum Dst is estimated to have been around -1,060nT.

Quebec Event - 1989

To date the most severe power system disturbance resulting from a geomagnetic storm occurred during the 1989 Quebec event which was a storm level K-9 event. This is the most well-known recent GMD experience in North America and it led to the collapse of the Hydro Québec system in the early morning hours of March 13, 1989. This severe geomagnetic storm caused the collapse of the Hydro-Québec power grid in a matter of seconds as equipment protection relays tripped in a cascading sequence of events. Six million people were left without power for nine hours, with significant economic loss. The storm even caused aurorae as far south as Texas. The geomagnetic storm causing this event was itself the result of a coronal mass ejection, ejected from the Sun on March 9, 1989. The minimum of Dst was -589 nT.

Bastille Day Event - 2000

On July 14, 2000, an X5 class flare erupted on the Sun (known as the Bastille Day event) and a coronal mass ejection was launched directly at the Earth. A geomagnetic super storm occurred on July 15–17; the minimum of the Dst index was – 301 nT. Despite the strength of the geomagnetic storm, no electrical power distribution failures were reported.

Halloween Event - 2003

Seventeen major flares erupted on the Sun between late October and early November 2003, including perhaps the most intense flare ever measured – a huge X28 flare, resulting in an extreme radio blackout, on November 4th. The GMD resulted in a blackout for several tens of minutes and left about 50,000 people without electricity in southern Sweden. In this same event termed the "Halloween storms of 2003," transformer heating and voltage fluctuations were observed in the Scottish Power network, but the effects remained at manageable levels. Transformers in the Eskom network in South Africa were also significantly damaged.

These flares were associated with CME events which impacted the Earth. The CMEs caused three geomagnetic storms between October 29th and November 2nd during which the second and third storms were initiated before the previous storm period had fully recovered. The minimum Dst values were -151, -353 and -383 nT. Another storm in this event period occurred on November 4 – 5 with a minimum Dst of -69nT. The last geomagnetic storm was weaker than the preceding storms because the active region on the Sun had rotated beyond the meridian where the central portion CME created during the flare event passed to the side of the Earth.

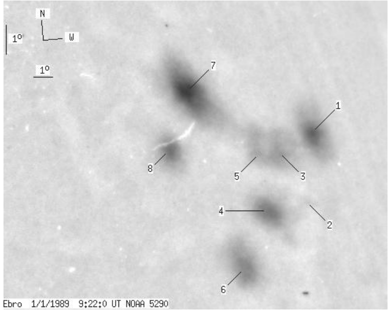
This storm was also associated with impacts in the southern hemisphere. For example, the GMD was associated with damage and lock out of a two-year old 90-MVA, 330-kV GSU transformer in Namibia. In South Africa, on-line dissolved gas analysis (DGA) measurements on numerous GSU transformers of unspecified designs/ages, showed an increase in gassing patterns immediately after the solar storm. Failures were experienced both during and after the GMD. An inspection of the failure evidence concluded that the failures were due to damage sustained during the GMD.

Chapter 1
Solar Weather

The Sun is an average star, similar to millions of others in the Universe. It is a prodigious energy machine, manufacturing about 3.8 x 10^{23} kW. In other words, if the total output of the Sun was gathered for one second it would provide the U.S. with enough energy, at its current usage rate, for the next 9 million years. The basic energy source for the Sun is nuclear fusion, which uses the high temperatures and densities within the core to fuse hydrogen, producing energy and creating helium as a byproduct. The core is so dense and the size of the Sun so great that energy released at the center of the Sun takes about 50 million years to make its way to the surface, undergoing countless absorptions and re-emissions in the process. If the Sun were to stop producing energy today, it would take 50 million years for significant effects to be felt at Earth!

The Sun has been producing its radiant and thermal energies for the past four or five billion years. It has enough hydrogen to continue producing for another 100 billion years. However, in about 20 billion years the surface of the Sun will begin to expand, enveloping the inner planets (including Earth). At that time, our Sun will be known as a red giant star. If the Sun were more massive, it would collapse and re-ignite as a helium-burning star. Due to its average size, however, the Sun is expected to merely contract into a relatively small, cool star known as a white dwarf.

The sun is characterized by solar cycles of approximately 11 years in length. This means that peak solar activity, and its potential impacts on the power grid on Earth, has occurred approximately every 11 years as long as the grid has been in existence. Actually the cycles occur in pairs, or phases. In the first phase, the sun's magnetic poles reverse polarity. In the second phase, the sun reverses the magnetic polarity again returning the poles back to its original polarity. Solar storm activity is strongly phase dependent and also very dependent on the position within the solar cycle.



Since 1755 when recording of solar sunspot activity began, 23 solar cycles have passed, and the current solar cycle 24 began in January 2008.

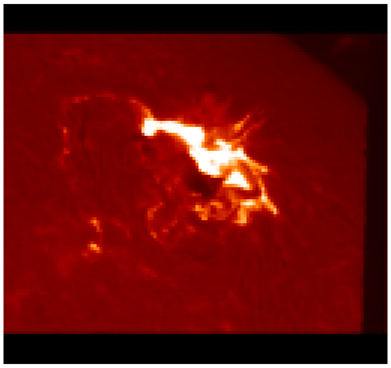
Sunspots and Solar Flares

Sunspots, dark areas on the solar surface, contain strong magnetic fields that are constantly shifting. A moderate-sized sunspot is about as large as the

Earth. Sunspots form and dissipate over periods of days or weeks. They occur when strong magnetic fields emerge through the solar surface and allow the area to cool slightly, from a background value of 6,000C down to about 4,200C; this area appears as a dark spot in contrast with the Sun. The rotation of these sunspots can be seen on the solar surface; they take about 27 days to make a complete rotation as seen from Earth. Sunspots remain more or less in place on the Sun. Near the solar equator the surface rotates at a faster rate than near the solar poles.

Groups of sunspots, especially those with complex magnetic field configurations, are often the sites of flares. Over the last 300 years, the average number of sunspots has regularly waxed and waned in an 11-year sunspot cycle. The Sun, like Earth, has its seasons but its “year” equals 11 of ours. This sunspot cycle is a useful way to mark the changes in the Sun. *Solar Minimum* refers to the several Earth years when the number of sunspots is lowest; *Solar Maximum* occurs in the years when sunspots are most numerous. During Solar Maximum, activity on the Sun and its effects on our terrestrial environment are high.

Solar flares result in supersonic plasma streams. These ionized atoms interact with charged particles in the earth’s atmosphere, inducing changes in the earth’s magnetic field. Normally, the earth’s field is relatively constant in magnitude, with a value of around 50,000 nanoteslas (nT) in North America. The bulk of the magnetic field is caused by an iron core at the center of the earth. This core is massive, almost equal in size to the moon, and its magnetic field is unaffected by the sun. However, the ionosphere and magnetosphere contain current paths. One of these currents is called an *electrojet* and runs east to west, approximately 60 miles in altitude, above the Northern Hemisphere magnetic pole. Solar events can cause changes in the earth’s magnetic field. These changes in turn produces an electric field at the surface.



A flare is defined as a sudden, rapid, and intense variation in brightness. A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. Solar flares are magnetically driven explosions on the surface of the sun. Approximately eight (8) minutes after a solar flare occurs on the surface of the sun, a powerful burst of electromagnetic radiation in the form of X-ray, extreme ultraviolet rays, gamma ray radiation and radio burst arrives at Earth. The ultraviolet rays heat the upper atmosphere which causes the outer atmospheric shell to expand. The x-rays strip electrons from the atom in the ionosphere producing a sudden increase in total electron content.

Radiation is emitted across virtually the entire electromagnetic spectrum, from radio waves at the long wavelength end, through optical emission to x-rays and gamma rays at the short wavelength end. The amount of energy released is the equivalent of millions of 100-megaton hydrogen bombs exploding at the same time!

As the magnetic energy is being released, particles, including electrons, protons, and heavy nuclei, are heated and accelerated in the solar atmosphere. The energy released during a flare is typically on the order of 10^{27} ergs per second. Large flares can emit up to 10^{32} ergs of energy. This energy is 10 million times greater than the energy released from a volcanic explosion. On the other hand, it is less than one-tenth of the total energy emitted by the Sun every second.

One **MeV** is one mega-electron volts or one million electron volts, and is a measure of energy. It is equal to $1.60217646 \times 10^{-13}$ joules.

There are typically three stages to a solar flare. First is the *precursor stage*, where the release of magnetic energy is triggered. Soft x-ray emission is detected in this stage. In the second or *impulsive stage*, protons and electrons are accelerated to energies exceeding 1 MeV. During the impulsive stage, radio waves, hard x-rays, and gamma rays are emitted. The gradual build up and decay of soft x-rays can be detected in the third, *decay stage*. The duration of these stages can be as short as a few seconds or as long as an hour.

Solar flares extend out to the layer of the Sun called the corona. The corona is the outermost atmosphere of the Sun, consisting of highly rarefied gas. This gas normally has a temperature of a few million degrees Kelvin. Inside a flare, the temperature typically reaches 10 or 20 million degrees Kelvin, and can be as high as 100 million degrees Kelvin. The corona is visible in soft x-rays, as in the above image. Notice that the corona is not uniformly bright, but is concentrated around the solar equator in loop-shaped features. These bright loops are located within and connect areas of strong magnetic field called active regions. Sunspots are located within these active regions. Solar flares occur in active regions.

Several systems are in use for measuring the intensity of solar flares. Older systems are based on the appearance of the flare through ground-based telescopes, while newer ones use data from spacecraft.

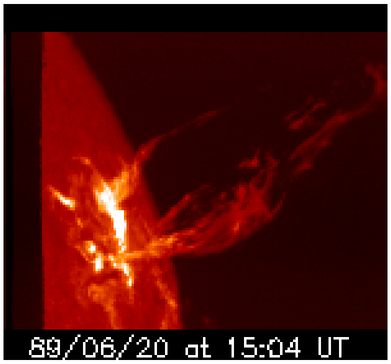
The most commonly used classification at present measures the maximum flux of X-rays (of wavelength 0.1 to 0.8 nanometer) produced by the flare. The approximate flux is indicated by a letter A, B, C, M, or X, with A being the weakest flares and X the strongest. (The letters C, M, and X stand for Common, Medium, and Extreme.) C-class flares are very small and produce few noticeable effects on Earth. M-class flares are medium-size and can cause brief radio blackouts in the polar regions. X-class flares are major events that can trigger worldwide radio blackouts and radiation storms in the upper atmosphere. Numbers after the letter, as in C6.2 or X14, measure the flux more precisely according to the scheme shown in the Table 2 below.

Table 2 Solar Flare Intensity		
	Maximum X-Ray Flux	
Flare Class	(W/m^2)	(erg/cm^2)
An	$n * 10^{-8}$	$n * 10^{-5}$
Bn	$n * 10^{-7}$	$n * 10^{-4}$
Cn	$n * 10^{-6}$	$n * 10^{-3}$
Mn	$n * 10^{-5}$	$n * 10^{-2}$
Xn	$n * 10^{-4}$	$n * 10^{-1}$

Examples: M4.2 = 4.2 x 10-5 W/m^2; X16 =16 x 10-4 W/m^2 = 1.6 x 10-3 W/m^2. For A, B, C, and M flares the value of" n" is between 1.0 and 9.9. For X scales the value of "n" is unlimited.

Coronal Mass Ejection (CME)

The outer solar atmosphere, the corona, is structured by strong magnetic fields. Where these fields are closed, often above sunspot groups, the confined solar atmosphere can suddenly and violently release bubbles or tongues of gas and magnetic fields called *coronal mass ejections*. A large CME can contain 10^{16} grams of matter that can be accelerated to several million miles per hour in a spectacular explosion. Solar material streaks out through the interplanetary medium, impacting any planet or spacecraft in its path. CMEs are sometimes associated with flares but usually occur independently.

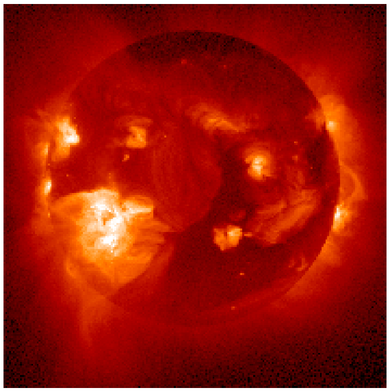


Although the Sun's corona has been observed during total eclipses of the Sun for thousands of years, the existence of coronal mass ejections was not realized until the space age. Coronal Mass Ejections disrupt the flow of the solar wind and produce disturbances that strike the Earth with sometimes catastrophic results.

Coronal mass ejections are often associated with solar flares but they can also occur alone. The frequency of CMEs varies with the sunspot cycle. At solar minimum we observe about one CME occurs per week. Near solar maximum an average of two to three CMEs occur per day.

Large flares are often associated with huge ejections of mass from the Sun. These coronal mass ejections (CMEs) are balloon-shaped bursts of solar wind rising above the solar corona, expanding as they climb. Solar plasma is heated to tens of millions of degrees, and electrons, protons, and heavy nuclei are accelerated to near the speed of light. The super-heated electrons from CMEs move along the magnetic field lines faster than the solar wind can flow.

Rearrangement of the magnetic field and solar flares may result in the formation of a shock that accelerates particles ahead of the CME loop. Each CME releases up to 100 billion kilograms of this material and the speed of the ejection can reach 1000 km/second in some flares. Solar flares and CMEs are the biggest "explosions" in the solar system.



When a CME strikes Earth, the compressed magnetic fields and plasma in their leading edge smash into the geomagnetic field like a battering ram. This causes a world-wide disturbance of Earth’s magnetic field called a geomagnetic storm. This produces a temporary disturbance of the Earth’s magnetosphere and an equatorial ring of currents, differential gradient and curvature drift of electrons and protons in the *Near Earth* region. A flood of charged particle and electrons in the ionosphere flowed from west to east, inducing powerful electrical currents in the ground that surge through natural rock. A pitch battle takes place between charged particles and magnetic fields that shake the Earth’s magnetic field over a period of several hours or days. The birthplace of CMEs are often seen to originate near the site of solar flares. Fast CMEs occur more often near the peak of the 11-year solar cycle, and can trigger major disturbances in Earth's magnetosphere, known as space weather.

Coronal holes are variable solar features that can last for weeks to months. They are large, dark areas when the Sun is viewed in x-ray wavelengths, sometimes as large as a quarter of the Sun’s surface. These holes are rooted in large cells of unipolar magnetic fields on the Sun’s surface; their field lines extend far out into the solar system. These open field lines allow a continuous outflow of high-speed solar wind. Coronal holes have a long-term cycle, but the cycle doesn’t correspond exactly to the sunspot cycle; the holes tend to be most numerous in the years following sunspot maximum. At some stages of the solar cycle, these holes are continuously visible at the solar north and south poles.

Solar proton event

A *solar proton event* (or proton storm) occurs when protons emitted by the Sun become accelerated to very high energies either close to the Sun during a solar flare or in interplanetary space by the shocks associated with coronal mass ejections. These high energy protons cause several effects. They can penetrate the Earth's magnetic field and cause ionization in the ionosphere. The effect is similar to auroral events, the difference being that electrons and not protons are involved.

Solar protons normally have insufficient energy to penetrate through the Earth's magnetic field. However, during unusually strong solar flare events, protons can be produced with sufficient energies to penetrate deeper into the Earth's magnetosphere and ionosphere. Regions where deeper penetration can occur include the north pole, south pole, and South Atlantic magnetic anomaly.

Protons are charged particles and are therefore influenced by magnetic fields. When the energetic protons leave the Sun, they follow the Sun's powerful magnetic field. When solar protons enter the domain of the Earth's magnetosphere where the magnetic fields become stronger than the solar magnetic fields, they are guided by the Earth's magnetic field into the polar regions where the majority of the Earth's magnetic field lines enter and exit.

Energetic protons that are guided into the polar regions collide with atmospheric constituents and release their energy through the process of ionization. The majority of the energy is extinguished in the extreme lower region of the ionosphere. This area is particularly important to ionospheric radio communications because this is the area where most of the absorption of radio signal energy occurs. The enhanced ionization produced by incoming energetic protons increases the absorption levels in the lower ionosphere and can have the effect of completely blocking all ionospheric radio communications through the polar regions. Such events are known as *Polar Cap Absorption* events (or PCAs).

The more severe proton events can be associated with geomagnetic storms that can cause widespread disruption to electrical grids. However, proton events themselves are not responsible for producing anomalies in power grids, nor are they responsible for producing geomagnetic storms. Power grids are only sensitive to fluctuations in the Earth's magnetic field.

Extremely intense solar proton flares capable of producing energetic protons with energies in excess of 100 MeV can increase neutron count rates at ground levels through secondary radiation effects. These rare events are known as *Ground Level Events* (or GLE's). Due to geomagnetic shielding solar energetic particles with energies less than 100 MeV can only reach the Earth’s atmosphere over Polar Regions where they lose their energy in collision with atoms in the atmosphere creating a cosmic ray shower of particles. If the particles have energies greater than 500 MeV, the cosmic ray shower can penetrate to the planet’s surface. SPEs take around an hour to reach Earth; however, the fastest measured SPE in recent times occurred on 20 January 2005 with an arrival time of 15 minutes.

Aurora

The aurora is a dynamic manifestation of solar-induced geomagnetic storms. The solar wind energizes electrons and ions in the magnetosphere. These particles usually enter the Earth's upper atmosphere near the polar regions. When the particles strike the molecules and atoms of the thin, high atmosphere, some of them start to glow in different colors. Aurora begin between 60 and 80 degrees latitude. As a storm intensifies, the aurora spread toward the equator. During an unusually large storm in 1909, an aurora was visible at Singapore, on the geomagnetic equator. The aurora provide pretty displays, but they are just a visible sign of atmospheric changes that may wreak havoc on technological systems.

Sequence of Events

Let's follow the sequence of events for a typical geo-magnetic disturbance. Geo-magnetic disturbances (GMDs) start with the sun. A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by a disturbance in the interplanetary medium.

The solar wind carries with it the magnetic field of the Sun. This field will have either a North or South orientation. If the solar wind has energetic bursts, contracting and expanding the magnetosphere, or if the solar wind takes a southward polarization, geomagnetic storms can be expected. The southward field causes magnetic reconnection of the dayside magnetopause, rapidly injecting magnetic and particle energy into the Earth's magnetosphere.

A geomagnetic storm is a major component of space weather and provides the input for many other components of space weather. A geomagnetic storm is caused by a solar wind shock wave and/or cloud of magnetic field which interacts with the Earth's magnetic field. The increase in the solar wind pressure initially compresses the magnetosphere and the solar wind's magnetic field will interact with the Earth's magnetic field and transfer an increased amount of energy into the magnetosphere. Both interactions cause an increase in movement of plasma through the magnetosphere (driven by increased electric fields inside the magnetosphere) and an increase in electric current in the magnetosphere and ionosphere. During the main phase of a geomagnetic storm, electric current in the magnetosphere create magnetic force which pushes out the boundary between the magnetosphere and the solar wind. The disturbance in the interplanetary medium which drives the geomagnetic storm may be due to a solar coronal mass ejection (CME) or a high speed stream, *co-rotating interaction region* (CIR), of the solar wind originating from a region of weak magnetic field on the Sun's surface. The frequency of geomagnetic storms increases and decreases with the sunspot cycle. CME driven storms are more common during the maximum of the solar cycle and CIR driven storms are more common during the minimum of the solar cycle.

A geomagnetic storm is defined by changes in the Dst (disturbance – storm time) index. The Dst index estimates the globally averaged change of the horizontal component of the Earth's magnetic field at the magnetic equator based on measurements from a few magnetometer stations. Dst is computed once per hour and reported in near-real-time. During quiet times, Dst is between +20 and -20 nano-Tesla (nT).

The size of a geomagnetic storm is classified as,

Moderate
-50 nT > minimum of Dst > -100 nT

Intense
-100 nT > minimum Dst > -250 nT

Super-storm
minimum of Dst < -250 nT

A geomagnetic storm has three phases: an initial phase, a main phase and a recovery phase. The *initial phase* is characterized by Dst increasing by 20 to 50 nT in tens of minutes. The initial phase is also referred to as a storm *sudden commencement* (SSC). However, not all geomagnetic storms have an initial phase and not all sudden increases in Dst are followed by a geomagnetic storm. The *main phase* of a geomagnetic storm is defined by Dst decreasing to less than -50 nT. The selection of -50 nT to define a storm is somewhat arbitrary. The minimum value during a storm will be between -50 and approximately -600 nT. The duration of the main phase is typically between two and eight hours. The *recovery phase* is the period when Dst changes from its minimum value to its quiet time value. The period of the recovery phase may be as short as eight hours or as long as seven days.

Solar coronal holes and coronal mass ejections (CMEs) are the two main categories of solar activity that drive solar magnetic disturbances on the Earth. Geo-magnetically induced currents (GICs) are produced only when a large CME occurs directed at the Earth. CMEs involve the ejection of a large mass of charged solar energetic particles that escape from the sun's halo (corona), traveling to the Earth in 15 hours to 4 days. These high-energy particles consist of electrons and coronal and solar wind ions.

When magnetic fields move in the vicinity of a conductor, such as a wire, an electric current is induced in the conductor. This occurs on a grand scale in a GMD. In this case, the moving magnetic field is generated by the electrojet, the electric current induced is the GIC, and the conductor is the Earth, power lines, etc.

One of the most important geomagnetic storm processes involves the intensification and flow of ionospheric currents known as electrojets. These electrojets are formed around the north and south magnetic poles at altitudes of about 60 miles and can have magnitudes of approximately one million amps, which is sufficient in intensity to cause widespread disturbances to the geomagnetic field. They vary with both position and time.

At the Earth, the charged particles from the CME interact with the Earth's magnetosphere-ionosphere system in a complex process that produces electrojets. Magnetic fields associated with these electrojets perturb the Earth's geo-magnetic field, inducing voltages in the transmission lines and causing GICs to flow (see Figure 3). These GICs flow in the Earth and on long man-made conducting paths that act as "antennae" (depending on the impedance) such as transmission lines, metallic pipelines, telecommunication cables, and railways. These quasi-DC currents can disrupt the normal operation of the power system and can, in some cases, damage equipment. Because of their proximity to the Earth's magnetic north pole, higher latitudes typically experience greater effects of GMDs.

However, a severe storm can affect equipment and systems even at lower latitudes.

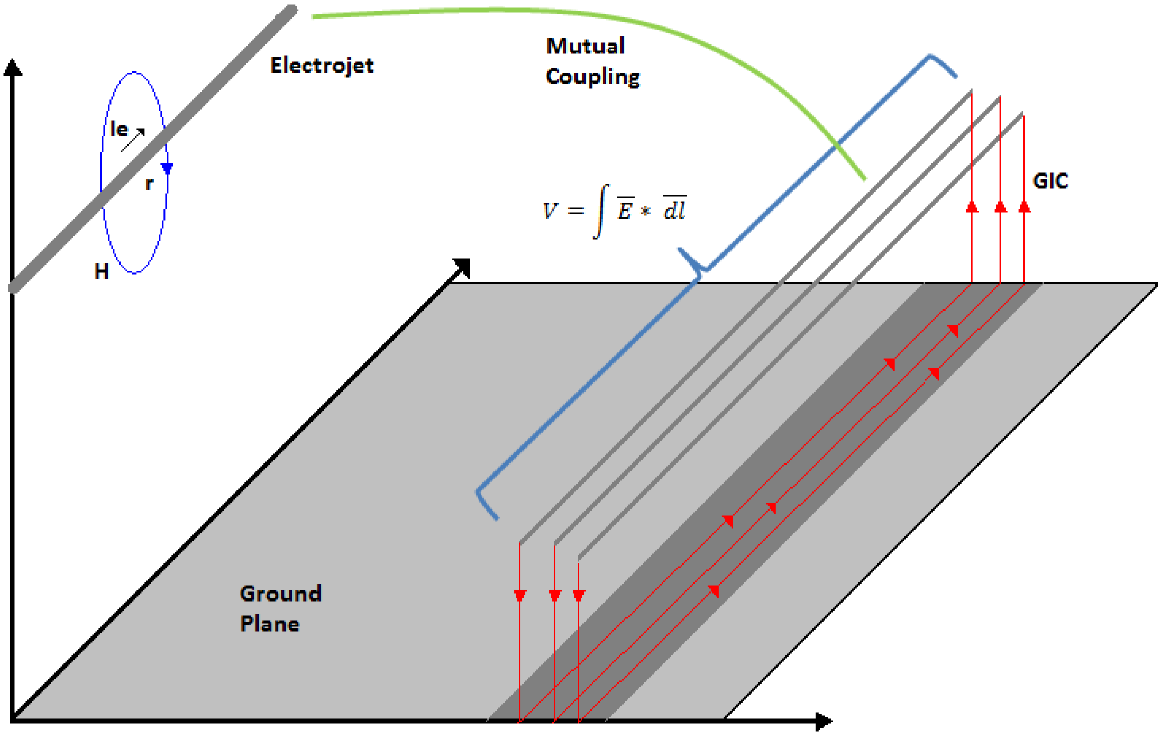


Figure 3

In summary, the chain of events that result in GICs is:

- A coronal mass ejection (CME) occurs at the sun.
- The mass of solar energetic particles travels to the Earth in 15 hours to 4 days.
- At the Earth, this mass of charged particles interacts with the Earth's magnetosphere-ionosphere system, producing varying electrojet currents above the Earth.

- Electrojet currents above the Earth produce changes in the geo-magnetic field.
- The changing geo-magnetic field induces voltage potential at the Earth's surface. The changing geomagnetic field is measured by the amount of change in amplitude of the magnetic field and the time required making the change measured in nano-Tesla per minute (nT/min).
- The voltage induced in the transmission lines drives geo-magnetically-induced currents (GICs).
- The GICs flow in the Earth and along conducting paths like power lines, potentially disrupting or damaging equipment.

On average, over an 11-year solar cycle, there are about 200 days when strong geo-magnetic storms occur, and about four days of extreme storms.

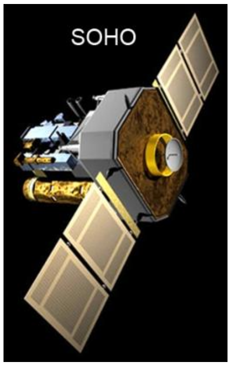
Chapter 2
Storm Prediction

This chapter summarizes the short-term prediction activities of the Space Weather Prediction Center in Boulder, Colorado. It also summarizes existing GIC monitoring activities and how this helps to inform longer-term prediction activities. For example, historical data on GICs can be compared to sunspot activity over a solar cycle. Project called Solar Shield is discussed, which aims to enhance space weather forecasting. The process of gathering data about impending GMDs is described, along with the process of disseminating alerts.

In the United States, the main source of space weather information is the Space Weather Prediction Center (SWPC) located in Boulder, Colorado. SWPC is a laboratory and service center of the National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service. According to the SWPC web site, it is “the nation’s official source of space weather alerts, watches, and warnings.” The SWPC provides both monitoring and forecasting of solar and geophysical events. To monitor events on the sun, SWPC scientists use various ground-based and space-based sensors and systems, as well as optical observatories around the world. SWPC forecasts space weather on time scales of hours to days by analyzing current conditions, comparing current conditions to past conditions, and using models.

Satellites

SWPC uses various existing satellites to monitor solar events, provide alerts, and aid forecasting. When used strictly for monitoring, they provide about a 40-60 minute warning before solar energetic particles from a CME reach Earth. These include the Solar and Heliospheric Observatory (SOHO), Advanced Composition Explorer (ACE), and Solar Terrestrial Relations Observatory (STEREO). The following is a brief explanation of each system.



SOHO

The Solar and Heliospheric Observatory (SOHO) is a project of international cooperation between the European Space Agency (ESA) and NASA to study the Sun, from its deep core to the outer corona, and the solar wind. SOHO is studying the Sun-Earth interaction from different perspectives.

SOHO was designed to answer the following three fundamental scientific questions about the Sun:

- What is the structure and dynamics of the solar interior?

- Why does the solar corona exist and how is it heated to the extremely high temperature of about 1,000,000C?
- Where is the solar wind produced and how is it accelerated?

Clues on the solar interior come from studying seismic waves that are produced in the turbulent outer shell of the Sun and which appear as ripples on its surface. SOHO is measuring the acceleration of the slow and fast solar wind, identifying the source regions and acceleration mechanism of the fast solar wind in the magnetically "open" regions at the Sun's poles, discovering new dynamic solar phenomena such as coronal waves and solar tornadoes, and revolutionizing the ability to forecast space weather, by giving up to three days notice of Earth-directed disturbances, and playing a lead role in the early warning system for space weather.

SOHO was launched by NASA in 1995 and moves around the Sun in step with the Earth, by slowly orbiting around the First Lagrangian Point (L1), where the combined gravity of the Earth and Sun keep SOHO in an orbit locked to the Earth-Sun line. The L1 point is approximately one million miles away from Earth (about four times the distance of the Moon), in the direction of the Sun. There, SOHO enjoys an uninterrupted view of the sun.

The **Lagrange** points are locations in space where the gravitational forces and the orbital motion of a body balance each other. There are five Lagrangian points in the Sun-Earth system, L1, L2, L3, L4, and L5. L1 is directly in line with the Sun-Earth axis, located about 1 million miles from Earth.

STEREO

The Solar TErrestrial RElations Observatory (STEREO) is the third mission in NASA's Solar Terrestrial Probes program. It uses two nearly identical space-based observatories - one ahead of Earth in its orbit, the other trailing behind - to provide stereoscopic measurements to study the Sun and the nature of its coronal mass ejections, or CMEs. The purpose of STEREO is to,

- Understand the causes and mechanisms of coronal mass ejection (CME) initiation,
- Characterize the propagation of CMEs through the heliosphere,
- Discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium, and
- Improve the determination of the structure of the ambient solar wind.

ACE

The Advanced Composition Explorer (ACE) is an Explorer mission that launched in 1997. The prime objective of ACE is to measure and compare the composition of several samples of matter, including the solar corona, the solar wind, and other interplanetary particle populations, the local interstellar medium, and galactic matter.

The spacecraft carries six high-resolution sensors and three monitoring instruments for monitoring samples of low-energy particles of solar origin and high-energy galactic particles.

ACE orbits the L1 LaGrangian. From its location at L1, ACE has a prime view of the solar wind, interplanetary magnetic field and higher energy particles accelerated by the Sun, as well as particles accelerated in the heliosphere and the galactic regions beyond.

ACE also provides near-real-time 24/7 continuous coverage of solar wind parameters and solar energetic particle intensities (space weather). When reporting space weather ACE provides an advance warning (about one hour) of geomagnetic storms that can overload power grids, disrupt communications on Earth, and present a hazard to astronauts.

Sunspot Progression

Examination of solar sunspot activity since the turn of the century shows the expected waxing and waning of activity over the last cycle (see Figure 4). Sunspots are dark, relatively cool areas (~4,200C rather than ~ 6,000C) on the solar surface with constantly shifting strong magnetic fields. Lasting for days or weeks, moderate sunspots are as large as the Earth and can be seen rotating as the sun spins on its axis once every 27 days.

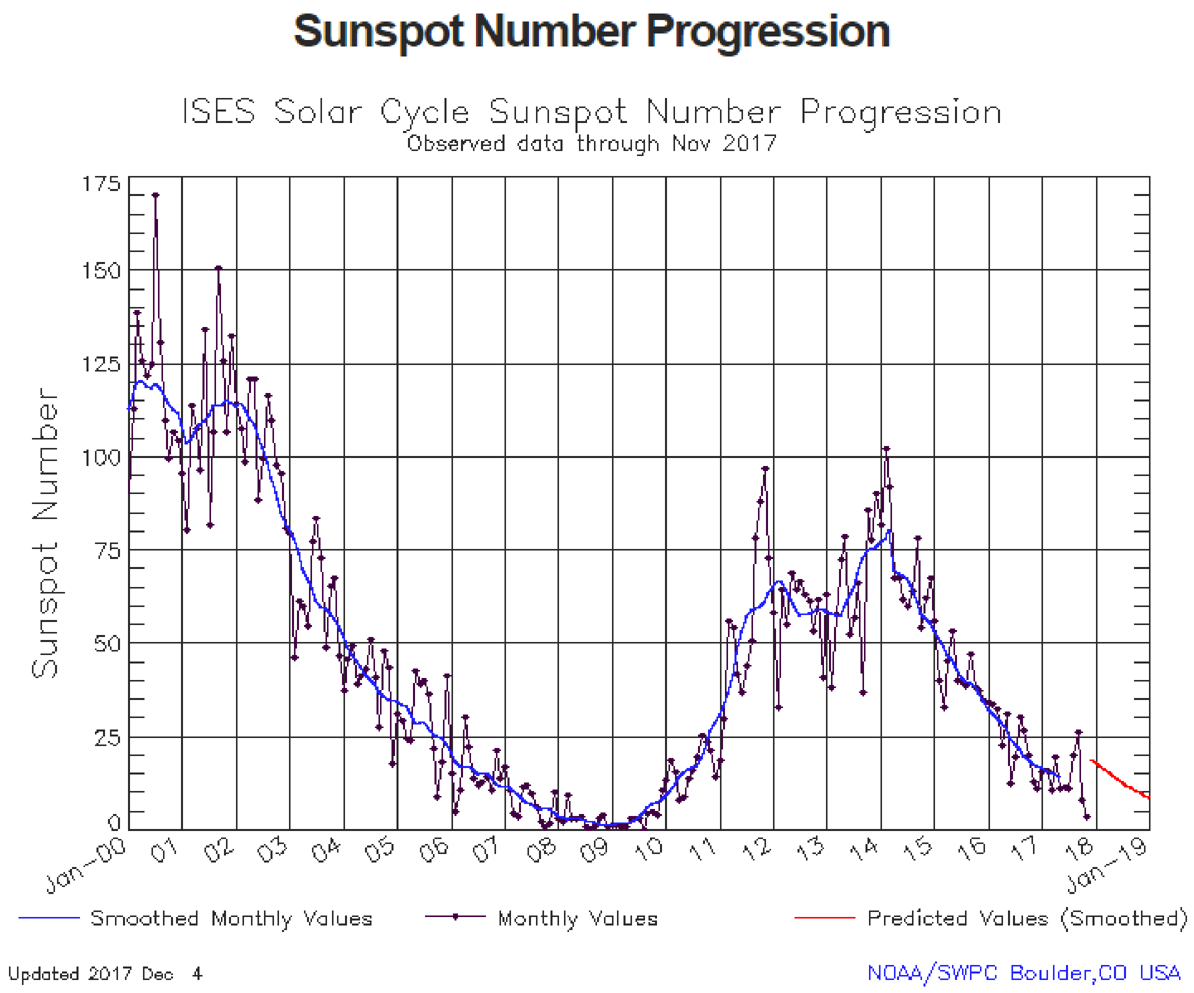


Figure 4

The last solar minimum (when the number of sunspots is lowest) occurred in December 2008, and that the solar cycle #24 maximum (when the number of sunspots is expected to be the highest) is forecast for May 2013. Solar cycle 24 began in January 2009. However, the number of sunspots in a given solar cycle does not necessarily correlate to the magnitude of the solar storms. Figure 5 illustrates the solar activity over the past 24 solar cycles.

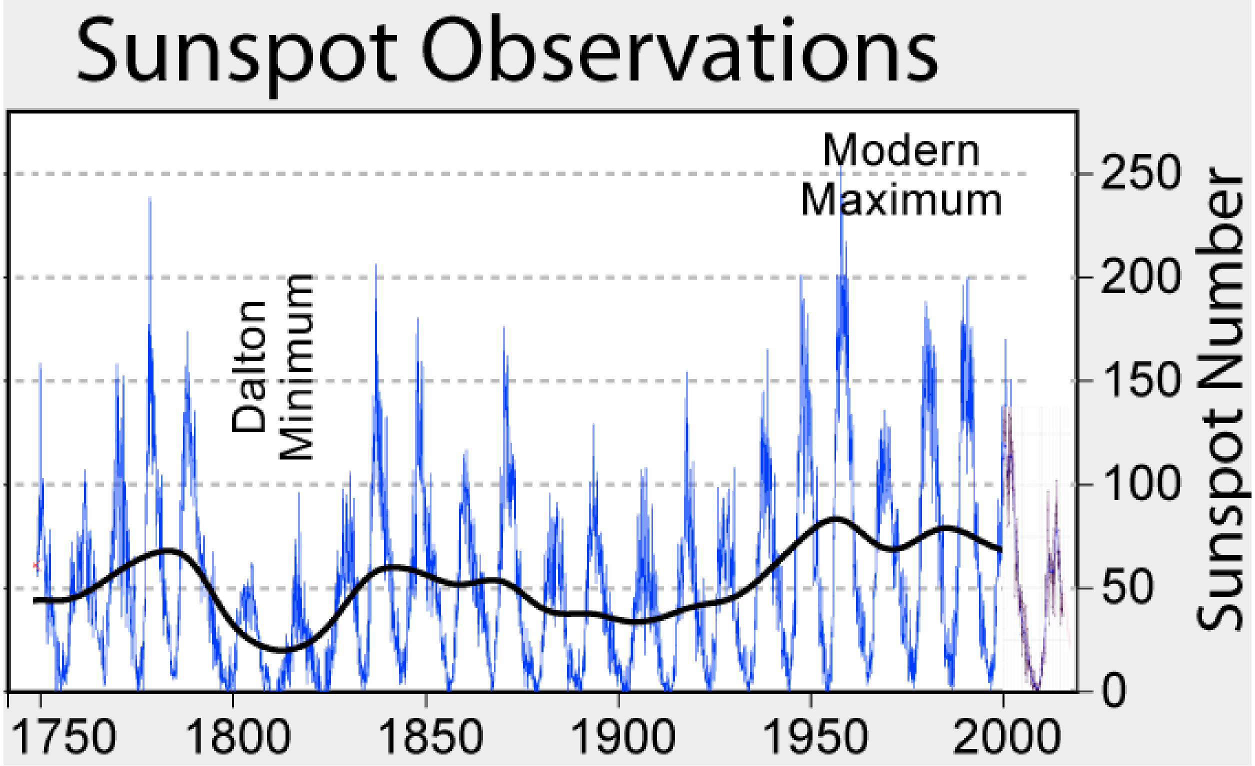


Figure 5

EPRI Sunburst Network

GIC monitoring is important to understand when and at what level GIC activity is occurring. Absent this information, implementation of GMD mitigating steps for power system operation can be based only on forecasting of solar activity along with real-time magnetometer information. Neither of these sources provides detailed information on GICs when a solar storm is occurring. Actual GIC measurements are extremely valuable because they confirm that a solar storm is occurring and provide a measure of storm severity.

Comprehensive GIC monitoring examines not just GICs as they occur, but also their impact on the grid in the form of harmonics, VAR consumption, losses, and transformer heating. This provides additional information on the impacts of affected transformers and the grid. Archiving the monitored GIC data allows for evaluation of equipment susceptibility to GICs and for post-event analyses to review misoperation of system protection or equipment failures. Post-event analysis is also useful for reviewing and refining operating procedures in light of recent solar storm experience.

The *EPRI Sunburst Network* is an example of a collaborative, nearly real-time GIC monitoring system that collects data from participating utilities and then makes the GIC data available online. Sunburst gathers data such as transformer phase currents, voltages, neutral currents, and hotspot temperatures, as well as electric and magnetic fields. Power system operators can view this GIC data during a solar storm and the sharing of GIC data provides a large area view of the storm (beyond a regional transmission system). Monitoring equipment alarms can be set for utility Supervisory Control and Data Acquisition (SCADA) systems. The Sunburst network provides automated e-mail alerts to system operators when a GIC event occurs.

Using the Sunburst network data, utilities can monitor their own GIC values in real time online and compare Earth currents for many other sites to gain a perspective concerning the magnitude and proximity of any unfolding solar storm. A utility's own monitoring sites enable them to read real-time harmonics from its transformers. This enables the utility to determine exactly when transformer half-cycle saturation occurs and when there is danger of damage. Pooling resources in a collaborative effort creates a core team that can maintain the power system and provide updates and alerts. In addition, Sunburst generates substantial new insights into how GICs progress during a solar storm – and how this data relates to prior observations from satellites or solar observations or predictions.

EPRI established the Sunburst Network in 1990, and the system recorded data over a period of nine years, from late 1990 to 1999, encompassing the end of solar cycle 22 and the start of solar cycle 23. In the year 2000, the network was upgraded and new data acquisition equipment was installed to provide a near real-time, online data feed to the central server. The updated system came online in spring 2000, in time to provide warnings and record GIC activity during strong solar storms that occurred on April 6-7, 2000. The system has operated continuously since that time, capturing data for the Halloween storms of 2003 for example.

Figure 6 plots Sunburst maximum neutral currents over the last two solar cycles on top of a plot of sunspot activity during the same period. In the figure, the number of sunspots is on the right hand axis and the left hand axis is the current amplitude (the maximum measured during the event) of the storms.

This plot shows that in these two recent solar cycles, the storms of any measurable magnitude have occurred during the storm season. The plot also shows that the major storms tend to occur on the back end, or downward slope of the storm cycle.

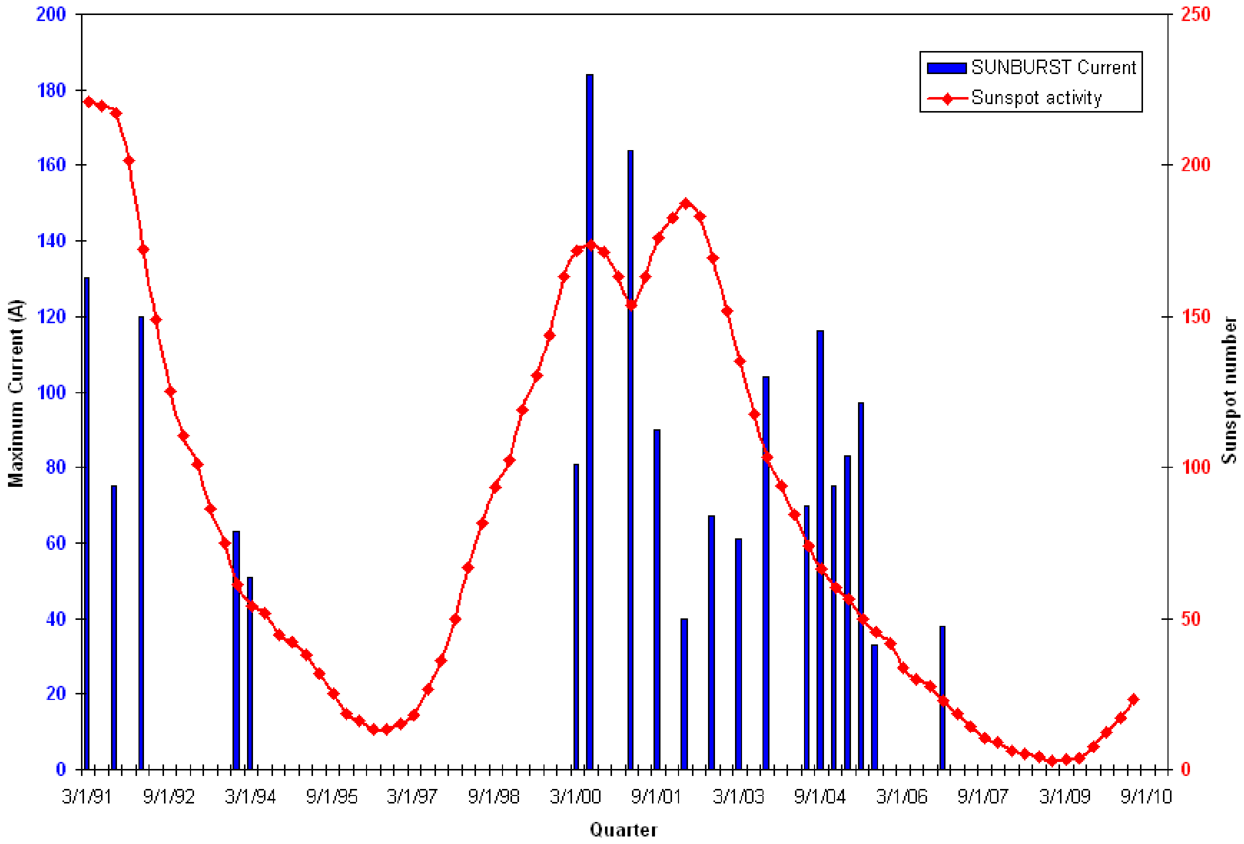


Figure 6

Examination of Sunburst data (during the Halloween storms of 2003) provided various insights. For example, while the event lasted five hours or longer, the large amplitude spikes were of short duration. Preliminary analysis concludes that these spikes have little impact on transformer heating due to long thermal time constants. A second observation is that there was a relatively long time period where a modest GIC of about 15 amps flowed. Currents at this level add to the heating of the transformer, but probably not to overheating. Transformer overheating is a function not only of the GIC magnitude and duration, but also the type of transformer and initial loading. One goal of the industry project is to develop sets of curves for types of transformers. For each type of transformer, the project aims to determine the estimated time to overload based on initial loading and GIC characteristics. A third observation is that the current changed direction from time to time during the event. A typical GMD phenomenon, the changing polarity has no relevance to saturation or heating.

Solar Shield

NASA and EPRI have collaborated to advance the field of space weather forecasting. “Solar Shield” is a NASA Applied Sciences project between the NASA Goddard Space Flight Center and EPRI. The goal of the three-year project is to design and establish an experimental forecasting system that can be used to help mitigate GIC impacts on high-voltage transmission systems. Solar Shield uses large-scale models that are based on first principles and hosted at the Community Coordinated Modeling Center (CCMC), which operates at the NASA Goddard Space Flight Center.

The *Solar Shield* project identified two-level forecasting system requirements, which led to development of two partly separate experimental forecasting products. The level 2 product, which provides a 15-60 minute lead-time, is based on in situ Lagrangian L1 point solar wind observations and magnetospheric magneto hydrodynamic (MHD) simulations. This means that the product is completely deterministic. The level 1 product, which provides a 1-2 day lead-time, is based on remote solar observations and heliospheric MHD simulations. As a result, the level 1 forecast is partly probabilistic. To generate level 2 GIC forecasts, Lagrangian L1 point solar wind observations from the NASA ACE spacecraft are used as inputs to a global magnetospheric MHD model. The team then uses the ionospheric current output of the MHD model to compute the GIC at individual transmission system nodes. The final output of the system is a text file of GIC forecasts, which is uploaded to the EPRI Sunburst Network. Participating utilities and other entities can access this network. The level 2 part of the system is currently only applicable to high-latitude locations. The project team recommends extending the forecasting system to cover lower latitudes in order to apply this approach to the U.S. power grid.

To generate level 1 GIC forecasts, the team inputs observations of solar CMEs to a heliospheric MHD model. The model then forecasts the interplanetary conditions at the Earth’s orbit as a result of the CME. The team applies an algorithm to these conditions to produce GIC forecasts at individual nodes of the power grid. Like the level 2 approach, the final output is a text file of GIC forecasts. These are also uploaded to EPRI’s Sunburst Network.

The EPRI Sunburst GIC dataset plays a critical role in the establishment of the forecasting system. The Solar Shield project team recommends installation of new GIC monitoring sites especially. This would enable expansion and increased utility of the newly developed GIC forecasting system.

Notifications

A satellite observes CMEs about eight minutes after they occur (because light travels the distance from the sun to the satellite in about eight minutes). When large solar flares are observed, SWPC issues solar flare radio blackout alerts. SWPC forecasters analyze observed CMEs to determine if they are directed toward the Earth, their speed, the anticipated strength of their impact on Earth, and the anticipated duration of the storm. The speed of the *solar energetic particles* (SEPs) ejected by CMEs varies, but the average speed is about one million miles per hour. Because the distance between the sun and the Earth is about 93 million miles, SEPs can take about 93 hours (about four days) to reach Earth, although significantly faster SEPs have been recorded (arriving as soon as 15 hours after ejection). This travel time allows some time for a forecasting process that can be based only on visual observation of the flare.

The SEPs pass the SOHO and ACE satellites at the L1 Lagrange point about 1 million miles from the Earth. At a speed of 1 million miles per hour, this occurs about one hour or less before the SEPs reach the Earth. The SOHO and ACE satellites obtain the first actual measurements of the solar wind speed, temperature, density, and magnetic field associated with the SEPs. Based on this information, if SWPC deems that a significant geo-magnetic storm is possible, it issues a geo-magnetic storm watch and subsequently, *sudden impulse warnings*.

SWPC may also issue geo-magnetic Kp-index warnings, based on the expected storm strength, and Kp-index alerts as Kp-index thresholds of 6, 7, and 8 are crossed. One measure of the intensity of a geomagnetic event is the K-index. Variations in the earth’s magnetic field is continuously measured at a several locations around the world and at the end of a three-hour period the variation in the magnetic field relative to a “quiet day” is converted into a K-number that ranges from zero to nine.

The Kp-index ranges from 4 to 9, indicating storms of increasing intensity (see Table 3). The Kp index is a weighted average of K indexes from a network of geomagnetic observatories. K indexes actually range from one to 9, but only Kp indexes between 6 and 9 generate alerts. The K index itself is a code that is related to the maximum fluctuations of horizontal components (nT) observed on a magnetometer relative to a quiet day, during a three-hour period.

Table 3

K Index, G Scale, and severity of potential power system impacts

K-Index K_P	Severity		Power System Impacts	Frequency (per cycle)
5	G1	Minor	Weak power grid fluctuations may occur.	1,700
6	G2	Moderator	Higher-latitude power systems may experience voltage alarms; long-duration storms may cause transformer damage.	600
7	G3	Strong	Voltage corrections may be required; false alarms triggered on some protection devices.	200
8	G4	Severe	Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.	100
9	G5	Extreme	Widespread voltage control problems and protective system problems may occur; some grid systems could experience complete collapse or blackouts. Transformers could be damaged.	4

At the low end of the scale, a Kp=5 storm is characterized by a 70-120 nT intensity, and weak power grid fluctuations are expected to occur. At the high end of the scale, a Kp=9 storm is characterized by a >500 nT intensity. In this case, "widespread control problems and protective system problems can occur; some grid systems could experience complete collapse or blackouts; and transformers could experience damage." The NOAA G-scale simply assigns a convenient scale of storm strength from G1 ("minor") to G5 ("extreme") to Kp index storms of 5-9, respectively, for simplicity.

The K-index is not a very useful indicator of how an intense storm will impact the electric system since it does not account for the rate of change associated with the variation. A K-9 storm that slowly changes the earth's magnetic field will have less impact than a K-9 storm with relatively fast variations. However, in general, geomagnetic storms with K-indexes of less than five don't seem to impact electric systems and there is some correlation to the K-index value and the severity of the impact on the electric system, though a K-8 storm may be worse than a K-9 because of the time varying characteristics.

Chapter 3
Risk to Electric Grid Components

Countries located in northern latitudes, such as Canada, the United States, and Scandinavia, are particularly vulnerable to geomagnetic storms. Power systems in these countries are more likely to experience significant geomagnetically induced currents because of their location in the northern latitudes, the soil type (igneous rock) surrounding electrical infrastructure, and the fact that transmission networks in these countries cover longer distances to the load center. Power systems located in the northern regions of the North American continent are also particularly vulnerable because of their proximity to the Earth’s magnetic north pole.

There are two fundamental risks that result from the introduction of GIC’s into the bulk electric system:

- Damage to equipment (primarily transformers), and
- Loss of reactive power support due to transformer core saturation

Geo-magnetically induced currents (GIC), affecting the normal operation of long electrical conductor systems, are a manifestation at ground level of space weather. During space weather events, electric currents in the magnetosphere and ionosphere experience large variations, which manifest also in the Earth's magnetic field. These variations induce currents (GIC) in conductors operated on the surface of Earth. Electric transmission grids are an example of such conductor systems. GIC also can cause problems, such as increased corrosion of pipeline steel and damaged high-voltage power transformers.

Electrical power transmission networks are vulnerable to geomagnetic storms as they span long distances to supply demand centers due to the use of high-voltage transmission lines. This is because the longer distances of networks make them better “antennas” to pick up the electrical currents induced by the geomagnetic storms. Geo-magnetically induced currents can also overload electrical power grids, causing significant voltage regulation problems and, potentially, widespread power outages. Moreover, geo-magnetically induced currents can cause intense internal heating in extra-high-voltage transformers, putting them at risk of failure or even permanent damage. Recent estimates state that 300 large extra-high-voltage transformers in the United States would be vulnerable to geo-magnetically induced currents. Damage to an extra-high-voltage transformer from geo-magnetically induced currents could take months or even a year to repair and cost in excess of $10 million.

A severe geomagnetic storm that disrupts the electric power grid at a regional, national, or international level affects not only the energy sector but also all the other infrastructure sectors that rely on electricity to carry out their mission. The economic impact of the loss of such critical infrastructure would be high; one estimate of the economic costs to the United States of the August 2003 blackout in North America (not due to an extreme geomagnetic storm) is $6 billion.

The Earth's magnetic field varies over a wide range of timescales. The longer-term variations, typically occurring over decades to millennia, are predominantly the result of dynamo action in the Earth's core. Geomagnetic variations on timescales of seconds to years also occur, due to dynamic processes in the ionosphere, magnetosphere and heliosphere. These changes are ultimately tied to variations associated with the solar activity (or sunspot) cycle and are manifestations of space weather.

The basic principle for the generation of GIC is that variations of the ionospheric currents generate an electric field driving GIC. A time-varying magnetic field external to the Earth induces electric currents in the conducting ground. These currents create a secondary (internal) magnetic field. As a consequence of Faraday's law of induction, an electric field at the surface of the Earth is induced associated with time variations of the magnetic field. The surface electric field causes electrical currents, known as geo-magnetically induced currents (GIC), to flow in any conducting structure, for example, a power grounded in the Earth. This electric field, measured in volts/kilometer (V/km), acts as a voltage source across networks.

Examples of conducting networks are electrical power transmission grids, oil and gas pipelines, undersea communication cables, telephone and telegraph networks and railways. GIC are often described as being quasi Direct Current (DC), although the variation frequency of GIC is governed by the time variation of the electric field. For GIC to be a hazard to technology, the current has to be of a magnitude and occurrence frequency that makes the equipment susceptible to either immediate or cumulative damage. The size of the GIC in any network is governed by the electrical properties and the topology of the network. The largest magnetospheric-ionospheric current variations, resulting in the largest external magnetic field variations, occur during geomagnetic storms and it is then that the largest GIC occur. Significant variation periods are typically from seconds to about an hour, so the induction process involves the upper mantle and lithosphere. Since the largest magnetic field variations are observed at higher magnetic latitudes, GIC have been regularly measured in Canadian, Finnish and Scandinavian power grids and pipelines since the 1970s. GIC of tens to hundreds of amps have been recorded. GIC have also been recorded at mid-latitudes during major storms. There may even be a risk to low latitude areas, especially during a storm commencing suddenly because of the high, short-period rate of change of the field that occurs on the dayside of the Earth.

Modern electric power transmission systems consist of generating plants inter-connected by electrical circuits that operate at fixed transmission voltages controlled at substations. The grid voltages employed are largely dependent on the path length between these substations and 200-

700 kV system voltages are common. There is a trend towards higher voltages and lower line resistances to reduce transmission losses over longer and longer path lengths. Low line resistances produce a situation favorable to the flow of GIC. Power transformers have a magnetic circuit that is disrupted by the quasi-DC GIC which occurs when the field produced by the GIC offsets the operating point of the magnetic circuit and the transformer may go into half-cycle saturation. This produces harmonics to the AC waveform, localized heating and leads to high reactive power demands, inefficient power transmission and possible mis-operation of protective measures. Balancing the network in such situations requires significant additional reactive power capacity. The magnitude of GIC that will cause significant problems to transformers varies with transformer type.

What is GIC?

When magnetic fields move about in the vicinity of a conductor such as a wire, a geo-magnetically induced current is produced in the conductor. This happens on a grand scale during geomagnetic storms. Long transmission lines are thus subject to damage by this effect. Notably, this chiefly includes operators in China, North America, and Australia, especially in more modern high-voltage, low-resistance lines. The European grid consists mainly of shorter transmission cables, which are less vulnerable to damage.

When charged particles in coronal mass ejections collide with Earth, they energize auroral electrojets. These electrojets are currents of multi-million amps or more that follow high altitude circular paths around the earth's geomagnetic poles in the magnetosphere at altitudes of about 100 kilometers. These high-altitude currents induce mirror currents near the Earth's surface. These mirror currents can flow into man-made conductors, like power transmission lines, pipelines, telecommunication cables and railroads tracks.

During a solar storm, as the CME plasma cloud collides with the planet; large transient magnetic perturbations overlay and alter the normally stable Earth's magnetic field. These magnetic perturbations are referred to as a geomagnetic storm and can affect the planet for a period of a day or two. These perturbations can induce voltage variations along the surface of the planet. Induce electric fields in the Earth create potential differences in voltage between grounding points—which causes Geomagnetic Induced Currents (GICs) to flow through transformers, power system lines, and grounding points. GICs can severely affect grounded wye-connected transformers and autotransformers through its Earth neutral connection.

The currents induced in these lines from geomagnetic storms are harmful to electrical transmission equipment, especially generators and transformers — inducing core saturation, constraining their performance (as well as tripping various safety devices), and causing coils and cores to heat up. This heat can disable or destroy them, even inducing a chain reaction that can overload and blow transformers throughout a system. This is precisely what happened on March 13, 1989 in Québec, as well as across parts of the northeastern U.S. when the electrical supply was cut off to over six million people for nine hours due to a huge geomagnetic storm. Some areas of Sweden were similarly affected.

According to a study by Metatech corporation, a storm with a strength comparative to that of 1921 would destroy more than 300 transformers and leave over 130 million people without power, with a cost totaling several trillion dollars. A massive solar flare could knock out electric power for months.

GICs can saturate transformer cores and cause internal heating that may lead to loss of transformer life or failure during a solar storm. The impacts are not confined to the transformer itself, but can affect the stability and power quality of the grid through significant increases in reactive power demand and distortions of the alternating current. Potential effects include overheating of auxiliary transformers, misoperation of protective relays, heating of generator rotors, and possible damage to shunt capacitors, static VAr compensators, and harmonic filters for high-voltage DC lines. Grid operations may also be impacted by solar storm effects on GPS systems and communications.

Based on Oak Ridge National Laboratory (ORNL) computer modeling of power system susceptibility to GMDs shows how geomagnetic storms affect the power grid. This report explains that the combination of longer line lengths and lower average resistances results in higher GICs for a given geo-electric field strength. This combination of attributes occurs primarily in extra-high voltage (EHV) transmission lines, rather than high voltage (HV) or medium voltage (MV) transmission lines. Hence, these EHV assets, which play a critical in bulk power transfer across North America, are more susceptible to GICs than the HV and MV transmission and distribution system.

This same trend applies to transformers. Because EHV transformers tend to exhibit lower winding resistance than HV or MV transformers, a higher GIC will result in the higher voltage transformers than the lower voltage ones, for a given geo-electric field strength. Like their transmission line cousins, these high voltage transformers are crucial to the reliable operation of the bulk power transmission system. In fact, the flow of GIC in transformers is the root cause of all power system problems, as the GIC causes half-cycle saturation to occur in the exposed transformers.

When induced current flows into the electrical power grid, it has the potential of overloading the grid and causing significant damage to critical components at power plants. Solar storms can cause major electrical blackouts that can affect millions of people over a large geographic area. The electrical power grid in the US is comprised of several elements. The electricity is generated in hydroelectric dams, coal/gas/oil fired power plants and nuclear power plants. The backbone of the electrical power grid is the high voltage transmission lines operating at 230kV, 345kV, 500kV and 765kV. These transmission lines and their associated transformers serve as the long-distance heavy hauling arteries of electricity in the United States. The electricity is transferred between power generators and regional substations on very heavy supply lines suspended on tall steel towers. At the regional substations the voltage is converted into lower voltages from 69,000 volts to 12,470 volts. The substations feed local communities generally using wood pole structures. The individual or neighborhood transformers steps the voltage down to 120/240-volts which supplies homes and businesses with electrical power.

The U.S. electric system includes over 6,000 generating units, more than 500,000 miles of bulk transmission lines (including lower voltage transmission lines), approximately 12,000 major substations, and innumerable lower-voltage distribution transformers. All can serve as potential GIC entry points from their respective ground connections. This enormous network is controlled regionally by more than 100 separate control centers that coordinate responsibilities jointly for the impacts upon real-time network operations. Figure 7 shows the total miles of high voltage transmission lines by voltage class.

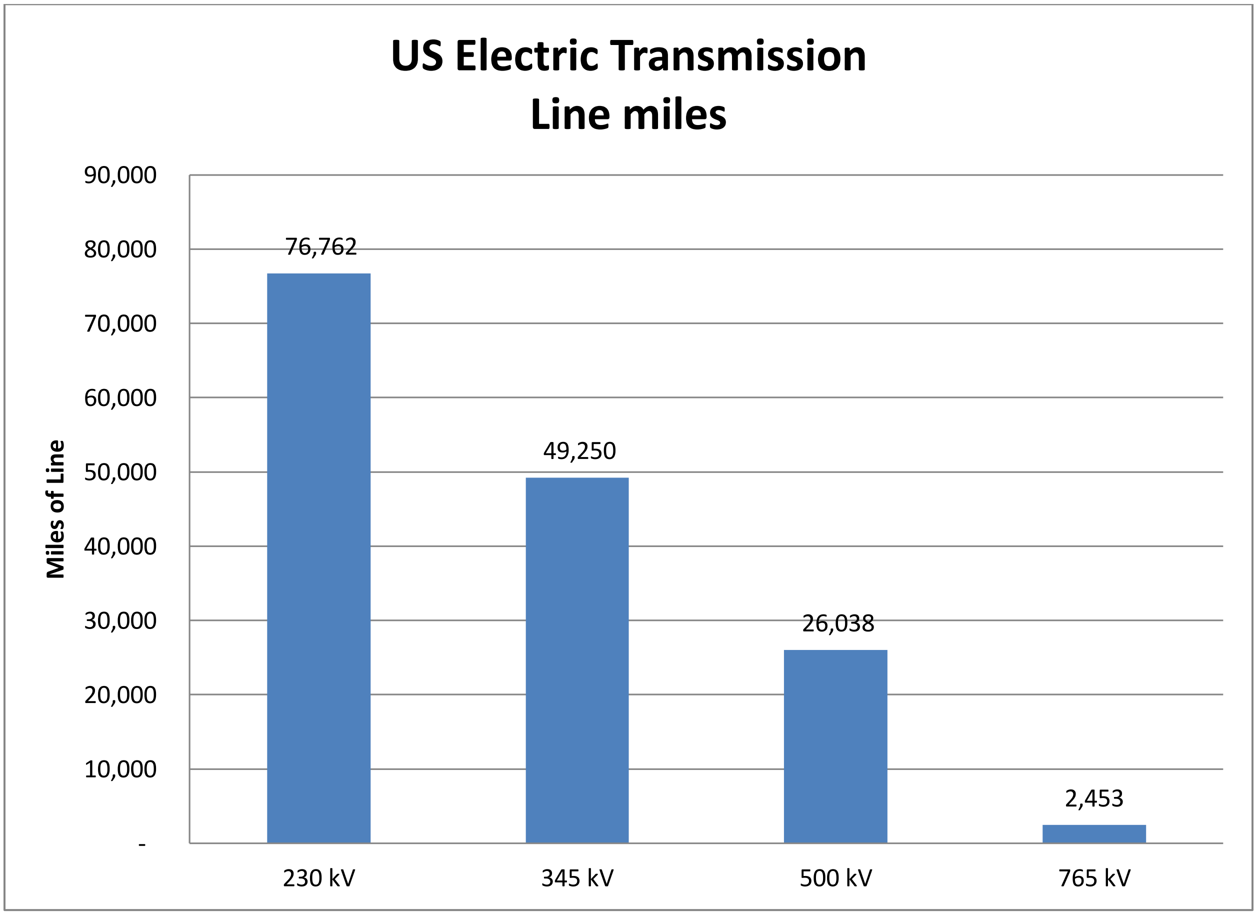


Figure 7

The susceptibility of electrical power grid to disruption and damage from solar storms is a function of:

- **Latitude** – The closer to the magnetic poles generally means the nearer to the auroral electrojet currents and as a result the greater the effect. The lines of magnetic latitude do not map exactly with the geographic latitude. The reason is due to the fact that the north and south magnetic poles are slightly offset from Earth's spin axis poles. As a result, East coast geographic mid-latitude is more vulnerable than the West coast geographic mid-latitude because the former is closer to the magnetic pole.

- **Strength of the Geomagnetic Storm** – Greater solar storms can move the auroral electrojet currents towards the equator and increase the intensity of the electrojets.

- **Earth Ground Conductivity** – Regions of low conductivity, such as regions of igneous rock geology, are more susceptible. Igneous rock is common over large portions of North America. If the power plant is located over a rock stratum with low conductivity, any geomagnetic disturbance will cause a bigger change in the voltage it induces in the local ground. This will result in larger GIC current flowing into the transformers. The Earth's conductivity varies by as much as five orders of magnitude.

- **Orientation** – Orientation of the power lines affects the induced currents. The gradients of earth surface potential are larger in the east-west direction. As a result, east-west oriented transmission lines are more susceptible than north-south lines.

- **Length** – The longer the transmission lines the greater the vulnerability.

- **Power Grid Construction** – The electrical DC resistance of transmission conductors and transformer windings, the transformer type and configuration, and method of station grounding can significantly affect vulnerability. Differential relay schemes on transformers are particularly susceptible to malfunction in the presence of GICs.

GIC Impact on Electrical Equipment

Let's now look at the impact of GIC on various electrical equipment used in the electrical utility industry. This includes a discussion of transformers, transmission lines, protective equipment, generators, circuit breakers, capacitors, and other equipment. The most susceptible equipment to GIC damage is probably the high-voltage transformers.

Transformers

Geomagnetic induced currents are a major concern for extra-high-voltage (EHV) grounded-wye transformer banks, which provide conducting paths for GIC's and zero-sequence currents. The presence of the quasi-DC GICs in the transformer windings cause half-cycle saturation or shift of the transformer operating range on the magnetization curve.

GICs also cause an increase in reactive power, or VAR, consumption by the transformers and an increase in even and odd harmonics which are generated by the half-cycle saturation. The half-cycle saturation of a transformer for a long enough time can cause stray flux to enter transformer structural tank members or current windings and produce overheating resulting in shortening of transformer lifespan or other permanent damage. GIC-induced can cause transformers to be vulnerable to thermal degradation and excessive gas evolution.

A plasma stream induces temporal and spatial variations in these upper atmosphere current paths, which induce magnetic field variations on the order of several hundred nanoteslas (nT), and the rate of change is up to tens of nanoteslas per second. By Faraday's law, a changing magnetic field induces an electric field. This electric field is modulated by the conductance of the earth. Lower conductance results in a larger field. For a typical solar storm, an electric field of a few V/km is induced. This field, often called a surface voltage potential, is slowly varying, or quasi DC, in nature. It is this field that drives power system GIC.

GICs can cause transformers to be driven into half-cycle saturation where the core of the transformer is magnetically saturated on alternate half-cycles. Only a few amps are needed to disrupt transformer operations. A GIC level induced voltage of 1-2 V/km and 5 amps in the neutral of the high-voltage windings may be sufficient to drive grounded wye-connected distribution transformers into saturation in a second or less. During geomagnetic storms, GIC currents as high as 184 amps have been measured in the United States in the neutral leg of transformers. The largest GIC measured thus far was 270 amps during a geomagnetic storm in Southern Sweden on April 6, 2000.

If transformer half-cycle saturation is allowed to continue, stray flux can enter the transformer structural tank members and current windings. Localized hot spots can develop quickly inside the transformers tank as temperatures rise hundreds of degrees within a few minutes.

Temperature spikes as high as 750F have been measured. As transformers switch 60 times per second between being saturated and unsaturated, the normal hum of a transformer becomes a raucous, cracking whine. Regions of opposed magnetism in the core steel plates crash about and vibrate the 100-ton transformers. GIC induced saturation can also cause excessive gas evolution within transformers. Besides outright failure, the evidence of distress is increased gas content in transformer oil; especially those gases generated by decomposition of cellulose, vibration of the transformer tank and core, and increased noise levels of the transformers.

GIC transformer damage is progressive in nature. Accumulated overheating damage results in shortening transformer winding insulation lifespan eventually leading to premature failure. In addition to problems in the transformer, half-cycle saturation causes the transformer to draw a large exciting current which has a fundamental frequency component that lags the supply voltage by 90 degrees and leads to the transformer becoming an unexpected inductive load on the system. This results in harmonic distortions and added loads due to reactive power or Volt-Ampere Reactive (VAR) demands. This results in both a reduction in the electrical system voltage and the overloading of long transmission tie-lines. In addition, harmonics can cause protective relays to operate improperly and shunt capacitor banks to overload. The conditions can lead to major power failures.

At the most basic level, a transformer consists of primary and secondary windings coupled via a magnetic core. Currents flowing in the windings produce alternating flux in the transformer core, and this time-varying flux provides the coupling between windings that results in the transformer action – stepping voltage up or down depending on the turns ratio.

When GICs flow through the transformer windings, they create a flux offset in the core. With sufficient offset, the crests of the flux waveform can exceed the saturation level of the ferromagnetic core material. The ease with which this saturation occurs depends on the B-H characteristic of the core material and, more importantly, the transformer core-winding construction.

The B-H characteristic (also called the magnetization curve, BH curve, or hysteresis curve) is a graph of the magnetic field B as a function of the magnetizing field H.

Look at Figure 8. The GIC causes a DC offset in the flux waveform, thereby increasing the flux waveform in the positive half cycle and decreasing the waveform in the negative half cycle. The normal core magnetizing current, $Im_{AC,}$ is below the saturation point of the core (i.e., Below the "knee of the curve".) However, when the GIC causes an offset in the waveform, the resulting magnetizing current, Im_{AC+DC} is in the saturated region of the core. Semi-saturation results in a significant increase in 60 Hz and harmonic components of the exciting current. The 60 Hz component of the exciting current results in an increase in the VAr demand of the transformer.

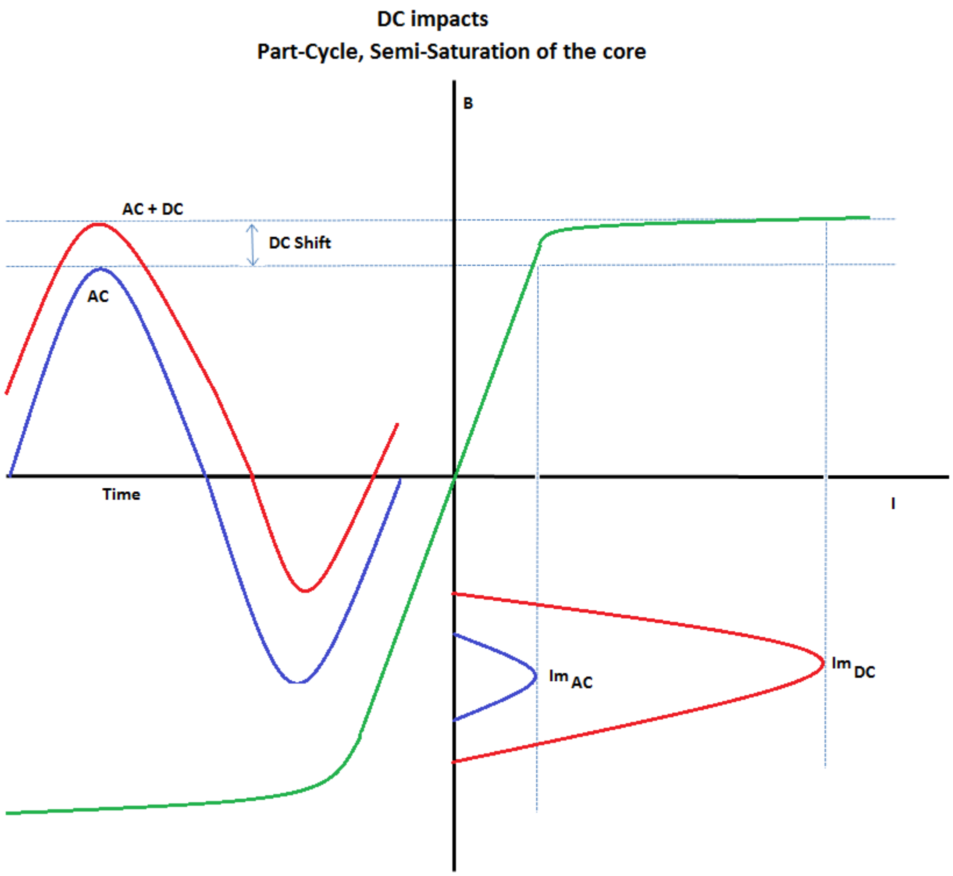


Figure 8

Single-phase transformers are the most vulnerable to semi-saturation because the DC flux has a low reluctance path through the core, as shown in Figure 9. Thus, semi-saturation can occur for relatively low levels of GIC.

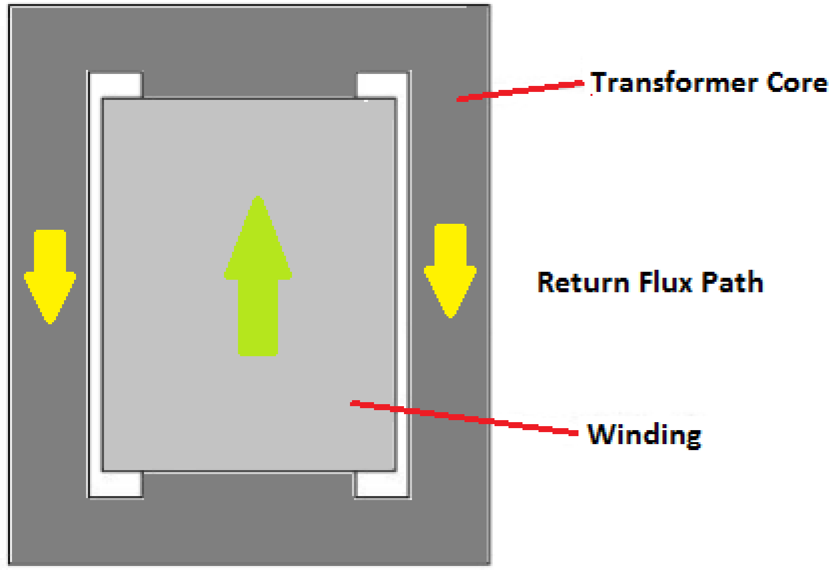


Figure 9

The transformer type that is the least susceptible to semi-cycle saturation from GIC is the three-legged core-form transformer, as shown in Figure 10. With equal GIC on each phase winding, the DC flux is all in the same direction, and there is no low reluctance return path in the core – the flux must return in air. Hence, a large GIC magnitude is needed to saturate the core in the winding area for this type of transformer construction.

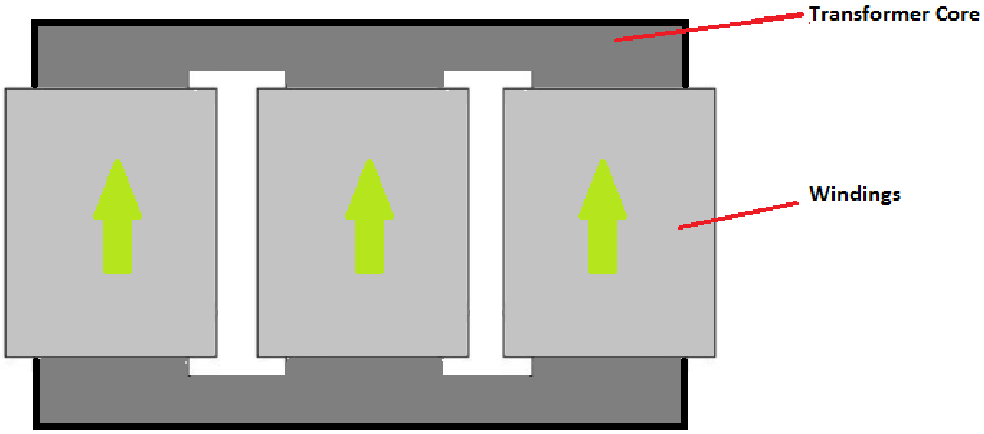


Figure 10

The susceptibility of transformers to GIC-induced saturation can be determined from the flux path of zero-sequence open-circuit excitation. As a result, the susceptibility of transformer banks to GIC-induced saturation can be categorized as either strong or weak. Three-phase and single-phase shell form, three-phase five-leg core form, and single-phase core form transformers are strongly susceptible. Three-phase three-leg core form transformers are weakly susceptible.

Depending on the return flux paths that the core construction provides, other transformer types are between the single-phase transformer and the three-legged three-phase core-form transformer in terms of vulnerability to GIC-caused semi-cycle saturation. In order of decreasing susceptibility to saturation, the other transformer types are seven-leg shell-form, three-phase conventional, and five-leg core-form. In a bank of single-phase transformers, saturation occurs in each phase independently. Saturation effects are more complicated in three-phase transformers due to the common flux paths in the core. For certain three-phase core-types, it is possible for the individual phase waveforms to be distorted differently.

When semi-cycle saturation occurs in a transformer, there are three main negative impacts: harmonics, heating, and increased VAr consumption.

- **Harmonics:** Semi-cycle saturation of the core produces all harmonics with magnitudes decreasing with harmonic order. These harmonics can cause mis-operation of protective relays, overloading of capacitor banks, and heating in generator rotors.
- **Heating:** During semi-saturation, magnetic flux extends out beyond the core into parts of the transformer where it would normally be negligible. The fringing fields can produce eddy current heating and magnetization losses, potentially causing localized hot spots in a transformer. The localized heating may cause damage to insulation, windings, leads, bracing, and tank walls. The heating may also cause gassing of the transformer oil. At the least, the localized heating causes accelerated aging of the transformer.
- **Increased VAR consumption:** Semi-cycle saturation in effect reduces the magnetizing reactance of the transformer thereby significantly increasing the 60 Hz component of the exciting current. This causes the transformer to appear as an inductive load on the transmission system. The resulting MVAr demand is dependent on the level of GIC and transformer type. During a solar storm, this increase in reactive loading can lead to voltage depression and in the worst case scenario, can disconnect transmission lines, initiate load shedding, or lead to system voltage collapse.

Generally, measured DC neutral current and the key indicators of saturation –harmonics and changes in transformer VARs – go hand in hand. Monitoring of DC neutral current provides a direct measure of GIC, but utilities can also monitor the impact of GICs by measuring at least the second harmonic of one phase on each side of a transformer.

The preferred method is to measure all phase currents and voltages with sufficient phase accuracy to calculate real and reactive power (VArs) for the transformer. Not only does this level of monitoring provide a view of the GIC impact during a solar magnetic disturbance, but it also provides information on transformer vulnerability.

Still debate in the industry with respect to the magnitude of damage GICs would cause in transformers (from slightly age to permanently destroy)

Transmission Lines

Electric fields are vectors with a magnitude and direction; values are usually expressed in units of volts/km; A 2,400 nT/minute storm could produce 5 to 10 V/km. The electric fields cause geomagnetically induced currents (GICs) to flow in electrical conductors such has the high voltage transmission grid. The magnitude of the DC voltage is determined by integrating the electric field variation over the line length.

Time varying magnetic fields induces an electric field. The magnitude of the electric field is a function of the earth conductivity structure of the earth, with lower conductivity resulting in higher electric fields. The resulting field induces a voltage in the transmission line via Faraday's Law,

$$V = \int E \cdot dL$$

where E is a vector representing the electric field, and dL is a vector representing the incremental length and direction of the transmission line. For most transmission lines, this equation can be estimated with reasonable accuracy using,

$$V = E \bullet (P_2 - P_1)$$

where, P_1 and P_2 are vectors corresponding to the positions, with respect to a fixed reference, of each end of the line. For GICs to flow in a transmission line, both ends of the transmission line must be connected to grounded transformers as shown in Figure 11.

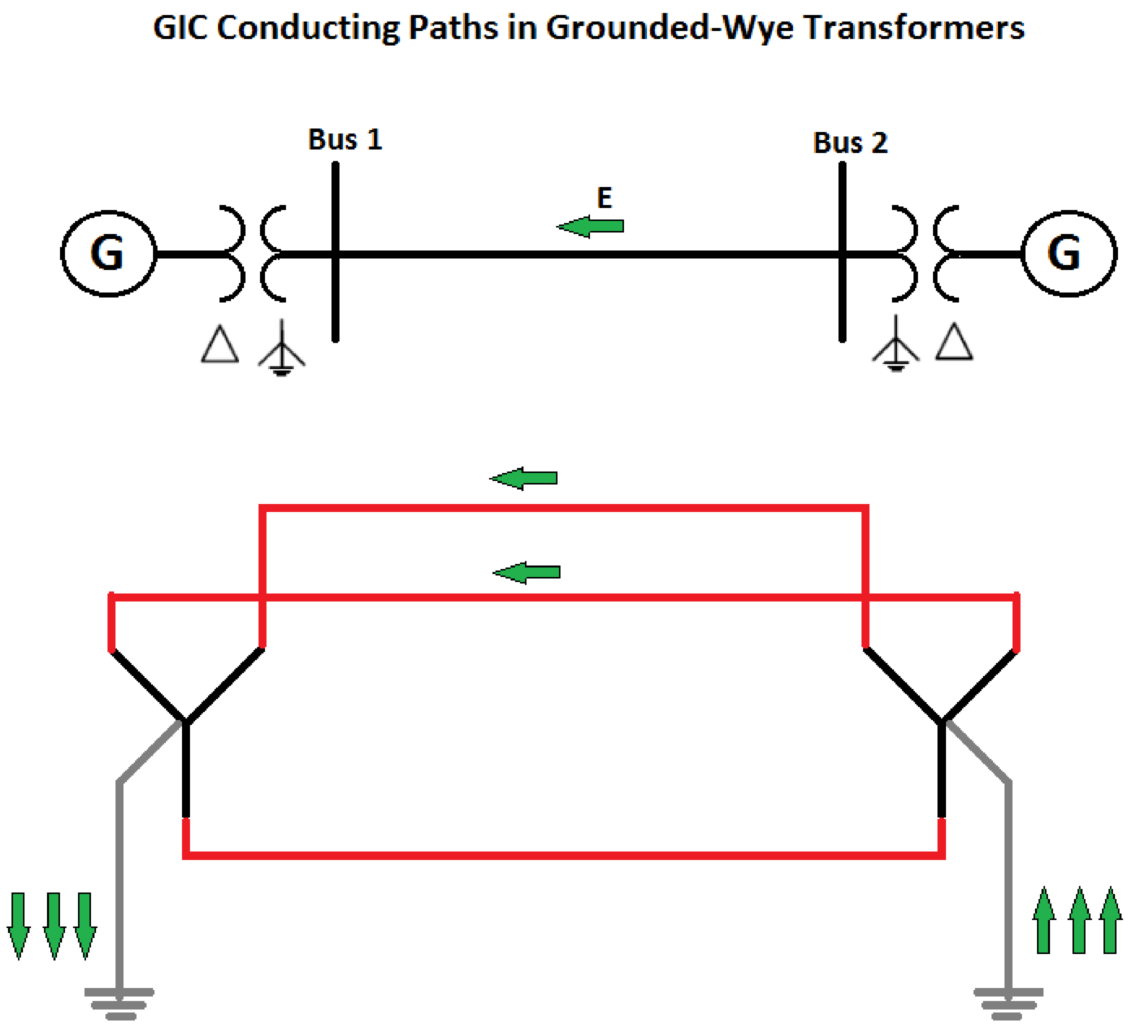


Figure 11

Figure 12 is a time plot showing measured GIC from the Sunburst network recorded during the start of a solar storm that occurred at the end of October 2003 (called the “Halloween storms”). Grid lines are at 15 minute intervals. The illustration shows that the GIC phenomenon is transient; albeit quite slow, with time scales on the order of tens of seconds to minutes. The plot also shows that GIC levels can swing dramatically from a peak in one direction to a peak in the opposite direction within tens of seconds.

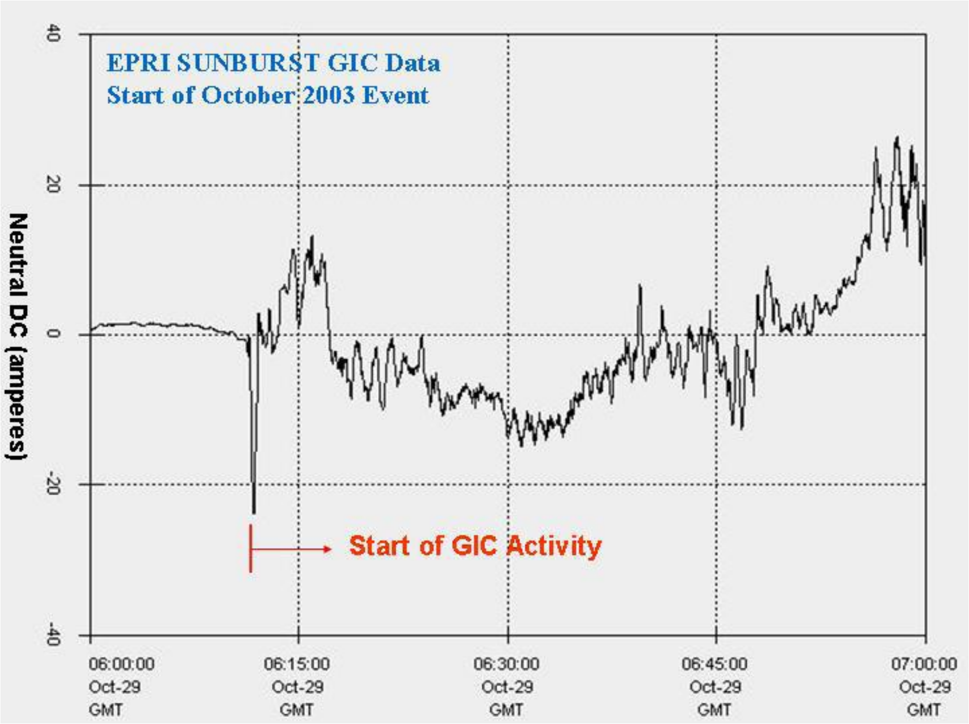


Figure 12

From a DC circuit standpoint, the magnitude of GIC current that flows is the induced voltage in the transmission line, divided by the total resistance. With a large interconnected transmission system, how GICs flow becomes a network problem, i.e. one cannot consider each transmission line independently.

During a solar storm, the electric field is continuously changing, and hence, not only does the GIC magnitude change continuously, but the direction changes as well. This changing magnitude and direction of GIC is visible in Figure 12.

For a short transmission line, the total resistance of the GIC path is typically dominated by the winding and ground resistances of the transformers. When the line is short, there may be little induced voltage.

Conversely, with a long transmission line, the resistance of the phase conductors becomes the dominant resistance, and the induced voltage may be significant. For example, a 60-mile transmission line in the direction of a 1-V/km electric field would have an induced voltage of 100-V to drive GIC. Electric field magnitudes during a GIC event typically range from 1 to 6 volts per kilometer (V/km) with continuously varying magnitude and direction.

The Earth’s geology plays a significant role in the magnitude of GICs. Electric fields, and hence induced voltages, are largest where the Earth conductivity is lowest, which is typically regions dominated by igneous rock. GIC flow may also be impacted by large bodies of water and the Earth's conductivity at the water boundaries.

To summarize, GICs are quasi-DC (i.e., slow transients with time constants on the order of tens of seconds or minutes) that are driven by induced voltages in the lines and typically change magnitude and direction throughout the duration of the storm. Depending on a transformer's construction, GICs flowing through the windings produce a flux offset that may cause semi-cycle saturation of the transformer core and disrupt normal transformer operation.

The operating voltage of the transmission network is an important factor in determining the level of GIC flow that will occur on each part of the U.S. power grid. At the higher operating voltages, there are pronounced which are: the average length of each line increases and the average circuit resistance decreases. These trends result in larger GIC flows in the higher voltage portions of the network, given the same geo-electric field conditions.

Protection Systems

Relay malfunctions are also an area of susceptibility to GMDs. Some older static or electromechanical relays that protect shunt capacitors and static VAR compensators operate on RMS quantities, and do not distinguish between fundamental and harmonic frequencies. Thus, harmonics generated from nearby semi-saturated transformers may cause these relays to misoperate. This removes from the system the valuable contribution of these capacitive devices; they are no longer able to compensate for the increased reactive power demand caused by the GICs. During solar cycle number 22, these relay failures contributed to power system problems. Microprocessor based relays utilize signal processing techniques that remove unwanted harmonic content, and; therefore capacitor banks and harmonic filter bank protection schemes that utilize these relays are not susceptible to misoperations caused by harmonics.

Transformer differential relays are vulnerable regardless of relay type. Harmonic restraint is often employed to protect against relay misoperation due to transient inrush currents. The scheme restrains the differential element whenever a particular level of 2nd or 5th harmonic current is measured by the relay. In the case of transformer inrush, this condition is temporary. However, in the case of a GMD event, the situation could last for a considerable period of time, e.g. hours. Depending on how the relay is set and the level of harmonic current, the differential element could be restrained throughout the GMD event. It is important for the relay engineer to evaluate the sensitivity of harmonic restraint settings to GMD events.

Generators

During a GMD event, voltage imbalance and harmonic distortion created by generator step up (GSU) transformer and local transformer half-cycle saturation can impact the generator. There have been documented cases of generator failure due to GMD and also evidence of rotor heating and protective relay operation, which could result in damage or loss of generation during a severe solar disturbance.

Potential generator susceptibility to GIC effects include:

- Increased negative sequence harmonic currents, resulting in increased generator heating due to oscillating rotor flux.
- Potential damage to rotor components, including retaining rings and wedges, due to prolonged negative sequence current and rotor heating.
- Increased mechanical vibrations and torsional stress due to increased negative sequence currents.
- Negative sequence relay alarming, operation, or erratic behavior due to harmonic content of the negative sequence currents.

Negative sequence overcurrent relays are not designed for the unique harmonic conditions posed by a geomagnetic storm. Therefore, the relays exhibit widely different responses to harmonics and they cannot, in general, be relied upon to protect against protracted high harmonic levels.

Current Transformers

Current transformers (CTs) and potential transformers (PTs) are affected by harmonics generated by the saturation of the instrument transformer cores. It is believed that differential relay schemes are particularly susceptible to malfunction in the presence of GICs.

Transformers that provide secondary current to the protective relay are primarily affected by GIC through the DC offset of measured currents. Assume the DC current will flow into the transformer neutral and will make its way onto the phase currents of the transformer, creating a DC offset on each phase that is some portion of the total DC current present at the transformer neutral.

If the affected transformer is a grounded delta-wye transformer designed for operation at 138/38 kV with a 100 MVA rating, the base current will be approximately 400 amps at rated power on the 138 kV wye-transformer. Assume a DC current of 30 amps is induced by the GIC on at least one phase of the wye transformer windings. Under normal operating conditions, the CT rating is selected to provide an accurate representation of symmetrical current up to 20 times nominal current. This is typically true for both the CT converting primary to secondary amps as well as the transformer within the relay converting secondary amps to a low-level current within the relay. Symmetrical load currents typically require only 5 percent of the total flux capacity of the CT. The DC offset from the 30 A of DC current created by the GIC consumes another 7.5 percent, leaving 87.5 percent of the flux capacity of the CT available to accurately represent phase currents. As the GIC continues in time, the DC offset is integrated into the total flux of the instrument transformer, so less and less of the total flux becomes available to reproduce the phase currents applied to the CT. If the GIC event duration continues with no change in the polarity of the GIC in the neutral of the transformer, CT saturation will eventually occur.

As far as the voltage measurement of transmission systems impacted by GIC is concerned, capacitive coupled voltage transformers (CCVTs) typically used for the measurement of voltages above 69 kV are immune to the effects of GIC.

Capacitors

High voltage shunt capacitor banks are generally used for reactive power compensation and voltage support during heavy loading conditions. The effect of harmonic currents generated during half-cycle saturation depends on a number of factors, such as the grounding configuration of the bank, protection scheme, and system impedance seen by the bank.

A shunt capacitor is a low impedance path for the harmonic currents generated during half-cycle saturation. Therefore, the RMS current flowing through the capacitor bank can increase substantially during a GMD event. Capacitor banks can withstand a certain amount of RMS overcurrent and overvoltage under normal and contingency conditions

Capacitors that are affected by GIC include grounded-wye shunt capacitor banks and capacitors used in static VAR compensator installations. A typical protection scheme for capacitor banks is an unbalance scheme using a current transformer in the capacitor bank’s neutral circuit. This protection scheme is designed to trip the capacitor bank when a given number of capacitor fuses have blown from the failure of individual capacitors. By tripping the capacitor bank, the protection scheme prevents excess voltage from being applied to the remaining capacitors in the bank, which can cause cascading failure of the remaining capacitors. However, some of these protection schemes also respond to any unbalanced or harmonic condition, and therefore will trip the capacitor bank during GICs.

Other issues with GICs in capacitors include, the amount of current flowing into capacitors depends on grounding. An ungrounded bank will see smaller RMS overcurrent than a grounded one because it blocks zero sequence harmonics. Intelligent electronic devices may be set to filter harmonics and, thus, be insensitive to harmonic overcurrents. A high voltage capacitor bank normally consists of a number of smaller series and parallel capacitor units in order meet nominal voltage and current specification. It is not uncommon for one or more of these to fail. If a sufficient number of units fail, the full capacitor bank is tripped off-line due to unbalance protection. If the bank is stressed due to harmonic overcurrents during a GMD event and there is no overcurrent protection, the bank is likely to trip on unbalance protection when a number of units fail. This would make the bank unavailable during the remainder of the GMD event, but would not result in irreparable damage to the bank. Replacement of damaged units is relatively simple and does not require a dedicated outage. Depending on the system impedance seen from the capacitor bank, the magnitude of the transformer's air-core reactance, and the magnitude of the GIC, a sustained resonance condition is possible. Such conditions would have to be evaluated on a case-by-case basis.

Shunt Reactors

Most shunt reactors used for reactive power compensation and voltage control on long, lightly loaded transmission lines do not have a steel core. These 'air-core' reactors do not saturate and are not affected by the effect of GIC and harmonics caused by half-cycle transformer saturation.

Circuit Breakers

In an inductive network, current can only be interrupted when it becomes zero during a 60 Hz cycle. A high voltage network is largely inductive, and circuit breakers designed to interrupt fault and load currents rely on a zero current crossing to initiate the process of successful arc quenching and current interruption.

If the magnitude of GIC is small compared to the magnitude of currents to be interrupted during a fault (a few hundred amps as compared to tens of kA under fault conditions), a zero crossing in the current to be interrupted will always take place. On the other hand, finding a zero crossing could be an issue if the magnitude of GIC exceeds the peak value of current in a lightly loaded circuit. In such a scenario, the arc between the poles of the circuit breaker would not be interrupted, and could be sustained for seconds or minutes and eventually damage the circuit breaker.

There are concerns about circuit breaker operation during GMD events including the possibility of increased secondary arc currents for single-pole switching on three-phase system, and increased breaker recovery voltages. Secondary arc current refers to the current that flows through a fault arc during a single-line-to-ground fault and after the opening of circuit breaker poles on the faulted phase. It is caused by electromagnetic and electrostatic coupling from the two energized phases. Single-pole switching of only the faulted phase improves system reliability by allowing the two un-faulted phases to remain energized and still transmit power. Normally, the secondary arc current is primarily fundamental frequency with some harmonic content. When GIC is present, however, the magnitude of the secondary arc current is considerably increased and the harmonic content of the current is increased. The increased magnitude of the secondary arc current caused by GIC increases the time needed for the arc to extinguish and increases the probability of a successful line reclosure for a given single-phase dead time. Dead time refers to the time between circuit interruption in the single-phase on the opening stroke and re-energization of the circuit on the reclosing stroke. Since GICs alter current zeros and the time interval between current zeros, the breaker recovery voltages can be excessive.

Surge Arrestors

Surge arresters are also susceptible to geomagnetic storms. Overvoltages caused by saturated transformers cause abnormal neutral overvoltages which may create a thermal runaway in the arrester.

Static VAR Compensators (SVCs)

Static VAR compensators provide fast-acting voltage regulation and reactive power compensation using thyristor-controlled capacitor banks. A GIC event would most likely saturate the coupling transformers in the SVC and transfer enough harmonics to the capacitor banks to cause the capacitor bank protection schemes to operate.

Distribution Systems

The primary impact of GIC's on distribution systems is blown fuses and some temporary overvoltages that may fail lightning. A GIC event could cause substation transformers to saturate, temporarily lowering the system voltage, which will cause the voltage regulators to increase voltage to compensate. The GIC will quickly subside and voltage regulators may not be able to respond quick enough to prevent a sustained overvoltage on the system.

Outage Scenario

The North American power system may be becoming more vulnerable to GMDs because of a ten-fold increase in EHV transmission miles, higher transmission voltages, longer interconnected lines, and the more recent slowing of transmission expansion, pushing these systems to operate closer to their limits.

A closer look at this concept reveals more insights into why today's power system may be more vulnerable than the system of even two or three solar cycles ago.

Voltage regulation plays a key role in assessing increasing vulnerability of the EHV transmission systems to GMDs. Increasing power transfers on the transmission network in recent decades have reduced reactive power reserves. To address this, power systems have added voltage regulation resources locally. In some cases, the margin of stability has been reduced. This means that a relatively minor voltage disturbance, if not identified and mitigated appropriately, could cause instability not only locally but could propagate across wide area power systems. While procedures are in place to mitigate voltage disturbances that occur periodically on power systems from a variety of sources, GMDs pose another potential source of voltage disturbance.

Would a GMD of given severity produce more severe impacts when power systems are operating at peak load or at light load? While one might think the answer is the former, some industry experts believe it is the latter, saying that a period of light load with high power transfer patterns is when the power system is most susceptible to GMDs. The reason is that failure of multiple facilities in this scenario would leave few mitigation options. Conversely, failure of the same number of facilities at peak load would be less impactful because almost all generators are running, and the contingencies could be mitigated using various emergency procedures and well-established practices. This light load scenario tends to occur in the middle of the night in the spring and fall. This is of concern because evidence shows that GMDs are more likely to occur in the spring and fall than the summer or winter.

Modeling of power grids and the impacts of GICs on power grid equipment has advanced to the point that analysts may be able to estimate the potential impact on the present power grid if a storm the likes of the 1921 GMD were to occur today. As related previously, estimation of the 1921 and 1859 storm activity, the resultant surface gradient, and GIC impact is difficult due to inadequate monitoring at the time of the older storms.

In the ORNL report, Metatech performed a modeling analysis of EHV transformers based on their understanding of historical storm magnitudes. The authors assumed a 4800 nT/min storm at 50-degree latitude with a homogeneous east-west direction and all lines in service. The minimum GIC amount that causes transformers to fail or incur damage is uncertain, but the study used 90 amps per phase as a base scenario – which may be an extreme value, but nevertheless, can be instructive as to the impacts of GMD.

Under this scenario, about 20 percent of 345-kV transformers, 28 percent of 500-kV transformers, and 32 percent of 765-kV transformers were likely to fail or be damaged. This represents a total of over 350 failed or damaged high-voltage transformers across North America in a short period of time (e.g., a few hours or days). Of these, the study estimated that a total of 94 generator step-up transformers in the northeastern region of the U.S. would be at risk of failure or damage. This is significant because loss of these transformers would not only impair transmission in this region, but also deprive the region of base-load power generation from large power stations in the area. In addition, the study estimated that such as a storm could place an additional almost simultaneous demand of over 100,000 MVARs on the power system.

Chapter 4
Mitigation Procedures

GIC risk can be reduced by capacitor blocking systems, additional generating capacity, and ultimately, load shedding. These options are expensive and sometimes impractical and the continued growth of high voltage power networks results in higher risk. This is partly due to the increase in the interconnectedness at higher voltages, connections in terms of power transmission to grids in the auroral zone, and grids operating closer to capacity than in the past.

By receiving geomagnetic storm alerts and warnings (e.g. by the Space Weather prediction Center; via Space Weather satellites as SOHO or ACE), power companies can minimize damage to power transmission equipment, by momentarily disconnecting transformers or by inducing temporary blackouts. Preventative measures also exist, including preventing the inflow of GICs into the grid through the neutral-to-ground connection.

This chapter summarizes the most likely approaches to block or reduce GIC flow in transformers and lines to mitigate GMDs. These include series compensation, use of blocking capacitors in the neutral ground, use of neutral resistors to reduce GIC flow as well as modifying operational practices. We will briefly cover each option.

Series Compensation

The most fundamental approach, though not necessarily practical based on system considerations, is to block the path of GICs. This would involve either the elimination of one of the two neutral ground connections at either end of a transmission line, inserting series compensation on the connected transmission lines, or use of a blocking capacitor in the neutral-ground connection. With any of these options, GICs cannot flow through the transformer windings, and the problems caused by semi-cycle saturation – namely harmonics, heating, and VAR consumption – are eliminated. Any blocking solution may significantly change the GIC impact to other parts of the system and can influence system operations.

Figure 13 shows a transmission line that is wye-connected at the left, and delta connected at the right. Because the transmission line is only grounded at one end, there is no path for GICs to flow. The most significant difficulty with this potential countermeasure is that single-phase autotransformers are the transformer of choice for bulk transmission at high-voltages due their high efficiency and low construction cost. Autotransformers are nearly always neutral-grounded to limit over-voltage problems. Thus, not only do they provide a ground connection for GICs, they also provide a through-path for GICs to flow from the high-side transmission line to the low-side transmission line, or vice versa.

Even if autotransformers are not used, a topology for always connecting a transmission line in the manner shown in Figure 13 – wye-connected on one side and delta-connected on the other side – is not always possible or practical based on system considerations. For example, a delta-wye connection introduces a specific phase shift, and the transformer connections must be made according to standard design to keep phasing consistent between the different voltages on the system (for interconnections).

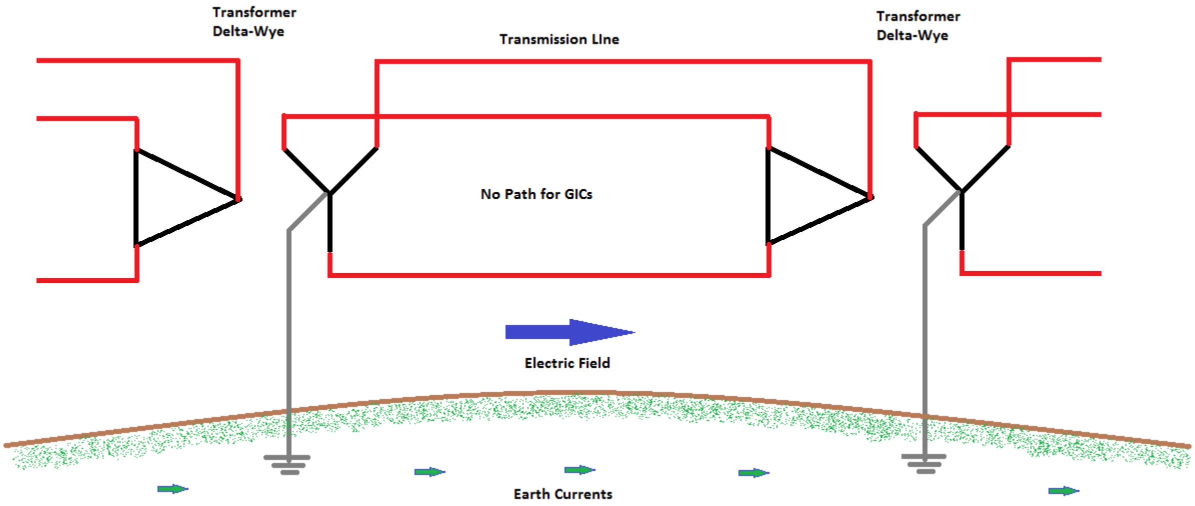


Figure 13

Because GICs are quasi-DC, capacitors are essentially an open circuit. Thus, two other blocking approaches involve the use of capacitors. In Figure 14, series compensation (capacitors) on the center transmission line phases blocks the flow of GICs. Note that in Figure 14, GICs are still shown flowing onto the autotransformer at the right and continuing on the transmission line to the right. For series capacitors, primary issues are line impedance, load impedance, and system stability.

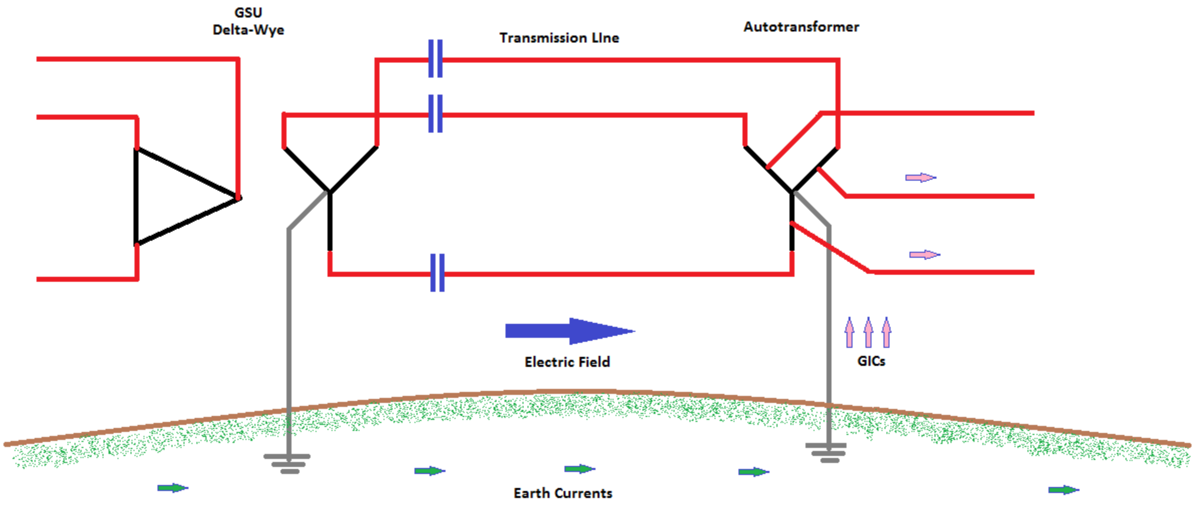


Figure 14

Implementation of series compensation on all three phases of all transmission miles would be exceedingly expensive.

> *In the Oak Ridge National Laboratory report, Metatech points out that the Western Electricity Coordinating Council (WECC) uses series compensation on about 55 percent of the miles of its 500-kV lines. Yet, a Metatech analysis shows that this region remains vulnerable to GMDs. The Metatech analysis of the WECC system showed that series capacitors there reduced overall GIC levels by 12-22 percent. Hence, Metatech concludes that "transmission line series capacitors applied on a limited and targeted basis do not appear to be an effective or likely economical choice for the reduction of GIC across the U.S. power grid, especially in the tightly interconnected eastern portions of the grid."*

Blocking Capacitors

In Figure 15, a blocking capacitor is applied to the neutral ground connection of a transformer. Note that the blocking capacitor is required only at one end of the transmission line to fully block GIC flow on that line. Again, however, GICs must be considered at the system level. Considerable efforts since the 1990s studied and demonstrated neutral ground blocking capacitors. The approach at that time was to implement the devices on a limited number of particularly vulnerable transformers, rather than more broadly as may be needed. However, widespread application of neutral capacitor devices would bring considerable uncertainty and risk of impedance changes and ferroresonance concerns on the network. Limited application of neutral capacitors would not be effective in mitigation concerns of wide spread catastrophic damage to key EHV transformers.

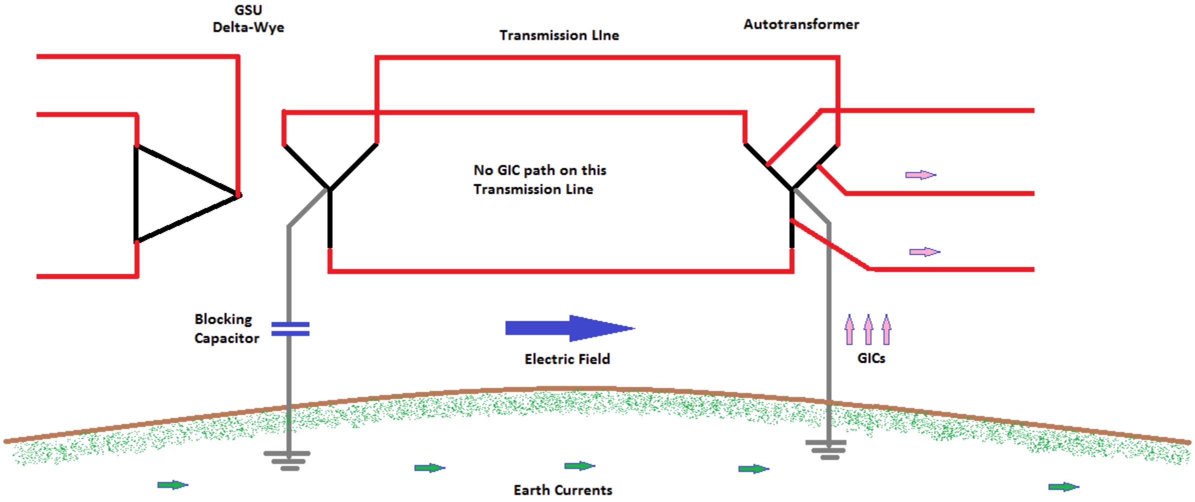


Figure 15

Neutral Resistors

One additional approach that reduces GICs is the use of a 2.5 to 7.5 ohm resistance in the ground connection (at the same location as the capacitor in Figure 15). This has been called a neutral grounding resistor or a neutral resistor/blocking device (NRBD), even though, strictly speaking, it does not fully block current flow. The reduction in GIC levels depends on the resistances – ground resistance, transformer winding resistances, and transmission line phase resistance – for the specific situation where it is applied, but typical levels that can be achieved are 60-70 percent reduction in GIC. The issues associated with this approach are identical to all of the issues that come with resistance grounding, namely selecting a ground resistance value based on fault current and relaying requirements.

An Oak Ridge National Laboratory (ORNL) study looked at IEEE guidelines to determine whether these resistors would alter grid grounding effectiveness. They concluded that use of low-ohmic resistors would probably not alter the grounding coefficients beyond these guidelines. According to the study the approach of using neutral resistors for GIC reduction does not appear to pose significant or insurmountable impediments.

Based on a preliminary cost estimate to retrofit EHV transformers in the U.S., it appears that the conceptual design of installing neutral resistors on the transformer neutral-to-ground connections is the preferred option of protection. Further studies are needed to determine the number and location of transformers that should be retrofitted, cost refinement, and finalize design requirements for the protection system. The impact on system protection schemes is also warranted.

Operational Practices

To mitigate the effects of a GMD event, the following operational techniques should also be considered:

- Reduce power output to increase margin on generator rotor field amps and allowable rotor heating.
- Dispatch additional local generation to reduce loading on a per generator basis and increase local reactive power capacity.
- Ensure that allowable negative sequence current is maintained within IEEE C50.13 limits with proper weighting, especially for second and other negative sequence harmonics that are present due to the transformer reaction to GIC. This could be done via operational practices or improved protective relaying design.

The effects on generators during a GMD event are coupled directly with the effects of local transformers driven into half-cycle saturation. By ensuring an adequate margin for rotor heating limits is present during an event, the generator operator can mitigate the permanent impacts of GMD on machine life. However for very large events, it may be necessary to protectively trip generating units to avoid potential damage and, in coordination, shed load in specific areas to alleviate the stress to remaining online generating units.

Conclusions

Severe GMDs are relatively rare events. Due to the growth in high voltage transmission systems over the last few decades that are now operating close to their limits, GMDs could pose a credible reliability risk. The greatest risk scenario involves widespread damage to high-voltage transformers and long recovery times. Reactive power loadings on hundreds of transformers could sky rocket, causing heating issues and potential large-scale voltage collapses, power system software like state estimation could fail, control room personnel would be overwhelmed, and the storm could last for days with varying intensity.

Procedures are in place to observe solar activity, measure the severity of Earth-directed solar activity at the L1 Lagrange point, and relay this information rapidly to interested parties. Capabilities are also in place to provide forecasts of potential GMDs in the form of warnings, alerts, and watches.

Technologies exist that can be retrofitted to transmission equipment to reduce vulnerability to GMDs such as neutral grounding resistors to reduce GIC flow in high-voltage transmission lines.

The following sources were used as references in developing this course.

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