United States Government Accountability Office

Report to the Committee on Homeland Security and Governmental Affairs, United States Senate

December 2018

TECHNOLOGY ASSESSMENT

Critical Infrastructure Protection

Protecting the Electric Grid from Geomagnetic Disturbances

GAO-19-98

The cover images depict electric power transmission equipment that can be affected by geomagnetic disturbances. On the left is a photograph of electric power transmission lines, in which geomagnetic disturbances can create geomagnetically induced currents. On the right is a photograph of a transformer, which can become the source of virtually all geomagnetic disturbance-induced issues on the electric power grid.

Cover sources (left to right): Department of Energy, Bonneville Power Administration; Department of Energy, Western Area Power Administration. | GAO-19-98

Highlights of GAO-19-98, a report to the Committee on Homeland Security and Governmental Affairs, United States Senate

December 2018

Why GAO did this study

Space weather refers to the impacts solar activity can have on the space environment, including the propagation of material that can cause electromagnetic events on Earth. When the space weather is severe, it can cause a large-scale GMD that may disrupt the reliable operation of the U.S. electric power grid.

GAO was asked to examine the availability of technologies that may mitigate the effects of large-scale electromagnetic events and the issues and challenges associated with the usage of such technologies. This report addresses: (1) what is known about the potential effects of GMDs on the U.S. electric grid; (2) technologies that are available or in development that could help prevent or mitigate the effects of GMDs; and (3) factors that could affect the development and implementation of these technologies.

GAO interviewed government and industry officials about potential GMD effects on the electric grid, including officials from 13 electric power suppliers that were selected based in part on their experiences preparing for and mitigating GMD effects. GAO reviewed technical studies identified through a literature review, as well as relevant Federal Energy Regulatory Commission orders and North American Electric Reliability Corporation (NERC) reliability standards.

GAO received technical comments on a draft of this report from seven federal agencies, NERC, and the Electric Power Research Institute, which we incorporated as appropriate.

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TECHNOLOGY ASSESSMENT

CRITICAL INFRASTRUCTURE PROTECTION

Protecting the Electric Grid from Geomagnetic Disturbances

What GAO found

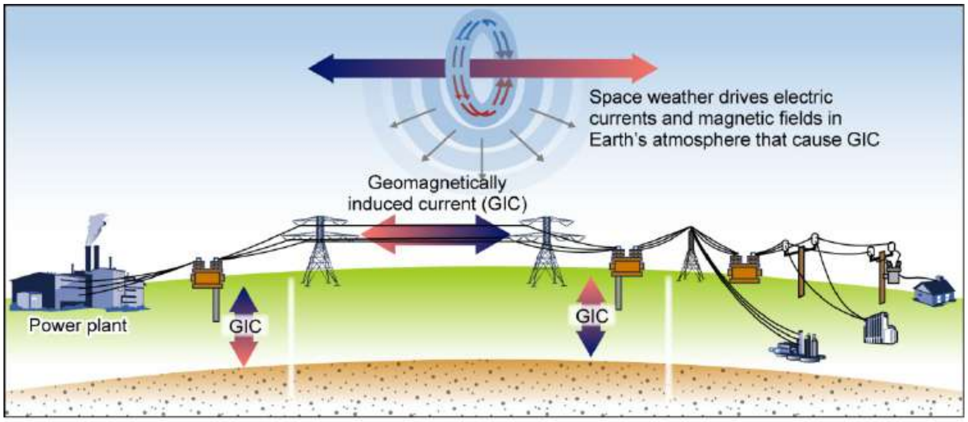
Geomagnetic disturbances (GMD), a result of space weather, pose a risk to the U.S. electric grid, although it is not clear how severe a risk. When GMDs occur, they can cause geomagnetically induced current (GIC) in the electric transmission grid, which can cause service disruption or damage under some circumstances (see figure). GMDs of varying levels occur regularly, but they rarely cause significant effects on the grid—either large-scale service disruptions or damage to electric grid equipment, particularly transformers. Since 1932, just four GMDs have significantly affected the grid worldwide. In the United States, the only significant effect of GMDs has been four transformers damaged at one power plant throughout 1989 with no loss in electric service.

While there is general consensus that GMDs pose a threat to the electric power grid, there are differing views on the scale and extent. Key factors affecting potential consequences include the magnitude of the space weather, the interaction between the space weather and Earth, and characteristics of the electric grid, including transmission line length and geographic orientation, as well as the response of transformers.

Technologies are available that may help limit the effects of GMDs on the electric grid. For example, certain currently used transformer designs can mitigate the effects of GIC on transformers. Further, some equipment currently in use can mitigate the effects of GMDs. For example, series capacitors, which are used to improve the capacity of long transmission lines, can eliminate GIC. One GIC-mitigating technology, neutral blocking capacitors, has been developed and operationally tested, but has not yet been widely deployed.

Federal policymakers face three broad questions that need to be addressed: (1) What is the likelihood of a large scale GMD? (2) What is the risk such storms pose to the electricity grid? and (3) What are potentially effective solutions to mitigate the effects of a large scale GMD? Efforts are under way to address aspects of each question that will help inform whether additional actions are needed to prevent or mitigate the effects of GMDs on the U.S. electric grid.

Geomagnetic disturbances can lead to geomagnetically induced current.



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

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Abbreviations

AC	alternating current
CME	coronal mass ejection
DC	direct current
DOE	Department of Energy
DHS	Department of Homeland Security
DSCOVR	Deep Space Climate Observatory
EPRI	Electric Power Research Institute
FERC	Federal Energy Regulatory Commission
GIC	geomagnetically induced current
GMD	geomagnetic disturbance
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Corporation
NOAA	National Oceanic and Atmospheric Administration
SWPC	Space Weather Prediction Center
USGS	U.S. Geological Survey

U.S. GOVERNMENT ACCOUNTABILITY OFFICE

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December 19, 2018

The Honorable Ron Johnson
Chairman
The Honorable Claire McCaskill
Ranking Member
Committee on Homeland Security and Governmental Affairs
United States Senate

Geomagnetic disturbances (GMD) are a result of space weather—conditions in the solar system that are driven by emissions from the sun. Solar emissions that are directed toward Earth interact with its magnetic field and can cause GMD that can disrupt the normal operations of a variety of technologies including satellites, communications networks, and navigation systems. The Aurora Borealis, or Northern Lights, is one of the most visible indicators of a GMD. When the space weather is severe enough, it can cause a large-scale GMD that could disrupt the reliable operation of the U.S. electric power grid. The reliability of the electric grid—the electric power generation, transmission, and distribution system comprising power lines and other infrastructure—has been a long-standing area of national interest.[1]

The Critical Infrastructures Protection Act of 2001 states that private business, government, and the national security apparatus depend on an interdependent network of critical physical and information infrastructures, including the energy sector, and establishes policy "that any physical or virtual disruption of the operation of the critical infrastructures of the United States be rare, brief, geographically limited in effect, manageable, and minimally detrimental to the economy, human and government services, and national security." It further defines the term ''critical infrastructure'' as "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters."[2] Subsequently, Presidential Policy Directive 21 on Critical Infrastructure Security and Resilience identified the energy sector, which includes the electricity sub-sector, as being uniquely critical due to the enabling function it provides across all critical infrastructure sectors.[3] It further defines several key roles for the federal government in the energy sector.

[1]The reliability of the electric grid is its ability to meet consumers' electric power demand at all times.

[2]The Critical Infrastructures Protection Act of 2001 was passed as part of the USA PATRIOT Act of 2001, Pub. L. No. 107-56, § 1016, 115 Stat. 272 (Oct. 26, 2001), *codified at* 42 U.S.C. § 5195c(b)(2),(c)(1), and (e).

[3]The White House, *Presidential Policy Directive/PPD-21: Critical Infrastructure Security and Resilience* (Washington, D.C.: Feb. 12, 2013).

The Department of Homeland Security (DHS) coordinates the overall federal effort to promote the security and resiliency of the nation's critical infrastructure, which includes the energy sector. The Department of Energy (DOE) has been designated the sector-specific agency for the energy sector, including the electricity sub-sector, and is responsible for collaborating with owners and operators of the energy infrastructure to strengthen the security and resilience of the sector. As part of its efforts, DOE also coordinates with DHS and other relevant federal departments and agencies and collaborates with applicable independent regulatory agencies. One such regulator is the Federal Energy Regulatory Commission (FERC), which among other responsibilities, regulates the interstate transmission of electric power and oversees the reliable operation of the bulk electric power system by establishing and enforcing mandatory standards that are developed by the North American Electric Reliability Corporation (NERC).[4]

The potential effects of space weather on critical infrastructure have received increasing attention in recent years. For instance, in 2011, the Strategic National Risk Assessment identified space weather as a hazard that poses significant risk to the security of the nation.[5] In 2015, the National Science and Technology Council issued a strategy and action plan to establish goals and guiding principles to enhance the national preparedness for space weather events.[6] The strategy is intended to support a collaborative and federally coordinated approach to developing policies, practices, and procedures to prevent or mitigate the effect of space weather on the nation's critical infrastructure. Further, by Executive Order No. 13744, on October 13, 2016, the President delegated the coordination of federal efforts to prepare the nation for space weather events to the Director of the Office of Science and Technology Policy.[7]

In 2016, we reported on the actions that key federal agencies had taken to address risks from electromagnetic events, including GMDs and nuclear high-altitude electromagnetic pulse, to the electric grid.[8] We found that DHS components had independently conducted some efforts to assess electromagnetic risk, but DHS had not fully leveraged opportunities to collect and analyze threat, vulnerability, and consequence information to inform comprehensive risk assessments of electromagnetic events. We also found that DHS and DOE need to do more to facilitate

[4]NERC, the federally designated U.S. electric reliability organization, is overseen by FERC. NERC is responsible for conducting reliability assessments and developing and enforcing mandatory standards to provide for the reliable operation of the bulk electric power system, which includes the facilities and control systems necessary for operating the interconnected electric power transmission network and certain generation facilities.

[5]Department of Homeland Security, *The Strategic National Risk Assessment in Support of PPD 8: A Comprehensive Risk-Based Approach toward a Secure and Resilient Nation* (Dec. 2011).

[6]Executive Office of the President, National Science and Technology Council, *National Space Weather Strategy* and *National Space Weather Action Plan* (Washington, D.C.: Oct. 2015).

[7]To carry out the coordination responsibilities, the Director is to consult with the Assistant to the President for Homeland Security and Counterterrorism and the Director of the Office of Management and Budget. Exec. Order No. 13744, *Coordinating Efforts to Prepare the Nation for Space Weather Events*, 81 Fed. Reg. 71573 (Oct. 18, 2016).

[8]GAO, *Critical Infrastructure Protection: Federal Agencies Have Taken Actions to Address Electromagnetic Risks, but Opportunities Exist to Further Assess Risks and Strengthen Collaboration*, GAO-16-243 (Washington, D.C.: March 24, 2016). A nuclear high-altitude electromagnetic pulse is the burst of electromagnetic radiation that results from the detonation of a nuclear device from about 25 to 250 miles above the Earth's surface.

government and private industry efforts to address the risks from nuclear high-altitude electromagnetic pulse, including conducting further research and development. In the report, we highlighted that technology may be able to mitigate the effects of electromagnetic events on the U.S. electric power grid.

We recommended, among other things, that DHS identify internal roles to address electromagnetic risks and collect additional risk inputs to further inform risk assessment efforts. We also recommended that DHS and DOE engage with federal partners and industry stakeholders to identify and implement key electromagnetic pulse research and development priorities. DHS and DOE concurred with our recommendations. As of October 2017, DHS had addressed our recommendation regarding key electromagnetic pulse research and development priorities by, among other things, working with key industry stakeholders to help identify and implement electromagnetic pulse research and development efforts. DHS had addressed our recommendation to take steps to identify key roles and responsibilities within the Department to address electromagnetic risks as well as work with federal and industry partners to collect additional inputs on threats, vulnerabilities, and consequences related to electromagnetic risks. DOE has also taken steps to work with industry to develop a joint government–industry electromagnetic pulse strategy and supporting DOE action plan to further address our recommendation regarding the identification of key electromagnetic pulse research and development priorities. Both DHS and DOE have reported taking some actions to identify critical electrical infrastructure assets, but have yet to fully address this recommendation. We will continue to review DHS and DOE's actions to address our open recommendations.

You asked us to examine the availability of technologies that could mitigate the effects of large-scale electromagnetic events and the issues and challenges associated with the usage of such technologies. In this report, we address (1) what is known about the potential effects of geomagnetic disturbances on the U.S. electric grid, (2) technologies that are available or in development that could help prevent or mitigate the effects of geomagnetic disturbances on the U.S. electric grid, and (3) factors that could affect the development and implementation of these technologies. We also discuss the strategic implications of the effects of geomagnetic disturbances on the U.S. electric grid.

To address all three research objectives, we met with federal agencies involved with GMDs and their effect on the electric power grid, including DHS, DOE and its national labs, the Department of Defense, FERC, the Department of the Interior's U.S. Geological Survey (USGS) and Bureau of Reclamation, the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC) within the Department of Commerce, and the National Aeronautics and Space Administration (NASA). We interviewed representatives from 13 U.S. and Canadian electric power suppliers—entities that own or operate generation or transmission infrastructure that conduct planning and generation, transmission, and distribution operations. We selected these 13 electric power suppliers based on input from DOE, NERC, electric power industry associations, and research institutions as to which suppliers had taken steps to prepare for and mitigate impacts from electromagnetic events. Of these 13 suppliers, we conducted site visits to 6 of them to supplement our understanding of the operation of the electric power grid, the potential effects that geomagnetic disturbances could have on the grid, and the prevention and mitigation strategies that are available to the suppliers when faced with a geomagnetic disturbance. We also met with electric power industry organizations, including NERC and manufacturers of electric power grid components. We met with researchers both in the federal government and in private industry to better understand technologies that are available or in development that can help prevent or mitigate geomagnetic disturbance effects.

We conducted a literature review and synthesized technical reports on geomagnetic disturbances and their effects with what we learned during our meetings to address the research objectives. We also reviewed FERC orders and NERC reliability standards that require certain suppliers to take steps to assess and prepare for GMD impacts. Additional details on our scope and methodology are contained in appendix I.

We conducted our work from February 2016 to December 2018 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

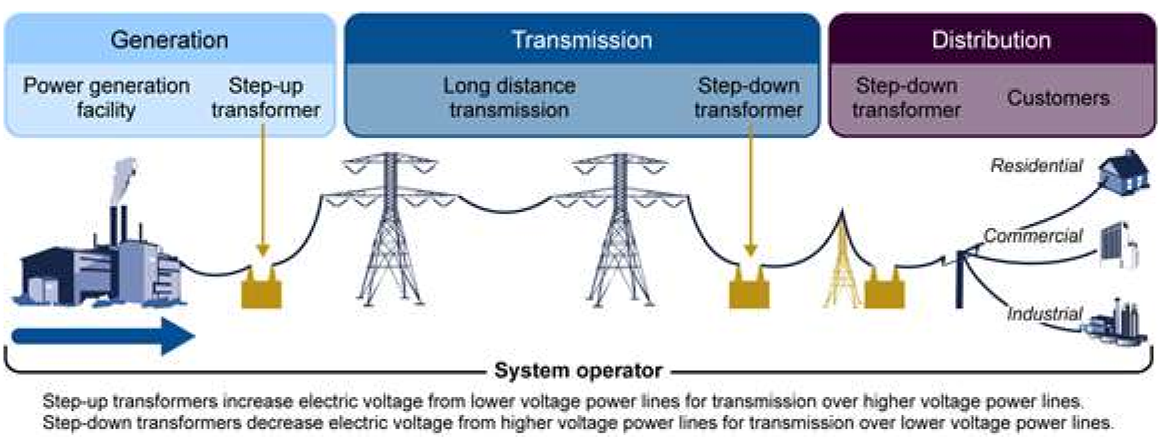
1.1 Operation and delivery of electric power in the United States

The U.S. electric grid comprises three distinct functions: generation, transmission, and distribution (see figure 1). Electric power is generated at power plants; can be transported over long distances using electric power transmission systems; and is sent to residential, commercial, and industrial consumers of electric power through distribution systems. Operation of the electric grid is managed by entities such as utilities and transmission operators, which are collectively referred to as system operators. Because electric energy is not typically stored in large quantities, system operators must constantly balance the generation and consumption of electric power to maintain system reliability. To do this, system operators utilize a system of sensors and controls to monitor power consumption and generation from a centralized location and manage adjustments in the output from power plants to match changes in consumption.

Generation: Power plants generate electric power by converting energy from other forms—using different types of fuels or energy sources—into electric power. The initial form of energy can be chemical (petroleum, natural gas, coal, etc.), mechanical (hydroelectric or wind), thermal (geothermal or solar), or nuclear. Power plants use generators to transform these initial energy forms into rotational mechanical energy and then into electrical power. Alternatively, radiant energy (solar) power stations use photovoltaic cells and power electronics to transform solar energy into electrical power.

Transmission: The power transmission system connects geographically distant power plants with areas where electric power is consumed. According to DOE, in the United States, the system includes approximately 240,000 miles of high-voltage, alternating current (AC) transmission lines between 230 and 765

Figure 1: Functions of the electric grid



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

kilovolts.[9] When electric power was first used in the United States in the 19th century, electric power needed to be used near generators. However, with the development of high-voltage, AC power transmission, power lines could transmit power over longer distances compared to the original direct current (DC) system. To transport electric power over long distances with minimal power losses, suppliers continued to increase the voltage of transmission lines. The installation of high-voltage transmission lines contributed to the expansion of the U.S. electric grid and encouraged the construction of higher-power generators to serve the growing electric power demands of the nation. Regional transmission systems above 200 kilovolts were initially used in the 1920s and evolved in the 20th century from point-to-point systems to rings, networks, and grids with geographically dispersed generation supplying load centers. The 1960s, in particular, was a period of growth in the transmission system above 300 kilovolts. Large, interconnected regional systems helped to accomplish technical and economic goals, including achieving economies of scale and the reliable delivery of electric power.

Today, according to DOE, approximately 3,350 distribution utilities are connected in one of three electric grids in the United States and extending into parts of Canada and Mexico: the Eastern Interconnection, Western Interconnection, and Electric Reliability Council of Texas (see fig. 2).[10] The interconnections are linked by a small number of high-voltage direct current connections that provide limited ability to move electric power between these systems. Otherwise, these three interconnections operate independently and electric power is produced within an interconnection to meet demand in the same interconnection.

Distribution: The final stage in the electric power system is the distribution system, which carries electric power out of the transmission system to industrial, commercial, residential, and other consumers.[11]

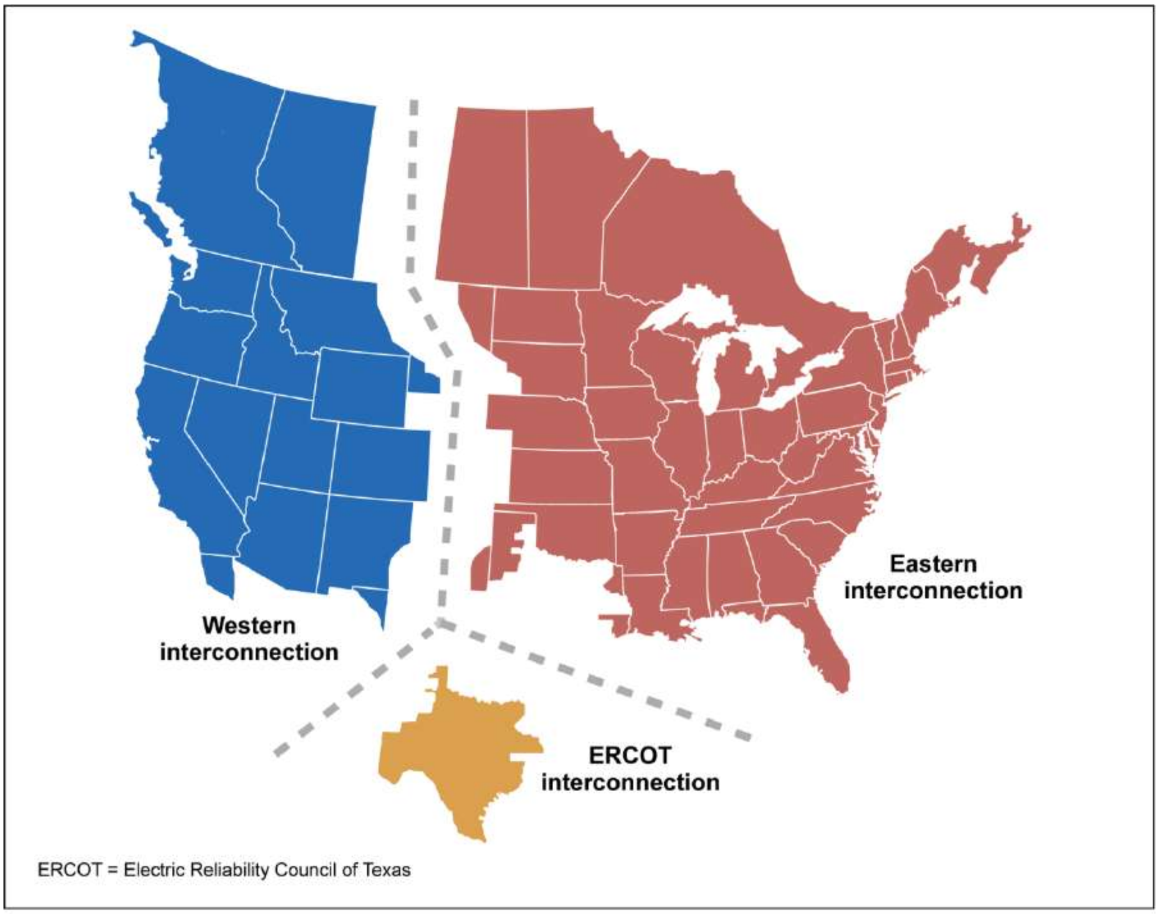
Responsibility for regulating the electric power system is divided between state governments and the federal government. Most electric power consumers are served by retail markets and intrastate distribution systems that are regulated by the states, generally through state public utility commissions or equivalent organizations. These state commissions approve many aspects of utility operations. FERC regulates the interstate transmission of electric power and provides for the reliability of the transmission system through the establishment and enforcement of mandatory standards. FERC reviews and approves mandatory standards developed by NERC, which is the federally designated electric reliability organization. NERC, which is subject to FERC oversight, is responsible for

[9]Department of Energy, Quadrennial Energy Review (QER) Task Force, *Transforming the Nation's Electricity System: The Second Installment of the QER* (January 2017). The volt is a unit of measurement for the electromotive force that causes electric power to flow through a conductor, with a kilovolt representing 1,000 volts.

[10]Quadrennial Energy Review 2017.

[11]According to the U.S. Energy Information Administration, the industrial sector encompasses manufacturing, agriculture, mining, and construction; the commercial sector consists of businesses, institutions, and organizations that provide services such as schools, stores, office buildings, and sports arenas; the residential sector includes households and excludes transportation; and other consumers include electricity users not captured in the other three categories, including transportation.

Figure 2: Three interconnected electric grids cover the contiguous United States



Sources: North American Electric Reliability Corporation (data) copyright © North American Electric Reliability Corporation. All rights reserved. GAO (presentation). GAO-19-98

conducting reliability assessments and developing and enforcing mandatory standards to provide for the reliable operation of the power transmission system, which includes the facilities and control systems necessary for operating the interconnected electric grid and certain power generation facilities. FERC, NERC, and NERC's Regional Entities all play a role in enforcement of reliability standards.[12] Within the boundary of each Regional Entity, there are one or more NERC-certified reliability coordinators that are responsible for assessing the real-time reliability of their designated parts of the transmission system. The reliability coordinator has the authority to direct electric power suppliers—transmission operators, generators, and others involved with the electric grid operations—to take action to preserve the reliability and integrity of the transmission system. NERC is also responsible for conducting periodic assessments of the reliability of the power transmission system.

[12]In 2007, FERC approved agreements by which NERC delegates its authority to monitor and enforce compliance with reliability standards to the eight Regional Entities.

One of the key objectives of DOE is to provide support for a more secure and resilient U.S. energy infrastructure. In particular, the Office of Electricity leads DOE's efforts to ensure a resilient and reliable electric power system and its Office of Cybersecurity, Energy Security, and Emergency Response leads DOE's emergency preparedness and coordinated response to disruptions. DOE and its national laboratories conduct research and assess risks to the electric power system and recommend measures to mitigate risks. In some regions of the country, DOE's four power marketing administrations sell and transmit electric power primarily from federally owned and operated hydroelectric power plants in 33 states.[13] These federal electric power suppliers usually own and operate transmission systems in their regions and are responsible for their reliable operation and subject to NERC reliability standards.[14]

1.2 Key components of electric transmission systems

Electric power substations are the hubs of the interconnected electric grid. They connect transmission systems with generators and with distribution systems. Step-up substations are used to increase the voltage of electric power from lower voltage lines for transmission over higher voltage lines. Step-down substations are used to decrease the voltage of electric power from higher voltage lines for transmission over lower voltage lines. Because electric power is generally produced at between 5 to 34.5 kilovolts and distributed at between 15 to 34.5 kilovolts, step-up and step-down substations are used as the entry and exit points, respectively, for electric power transfer through the high-voltage transmission system. There are a range of transmission line voltages in the United States and step-down substations are used to decrease the electricity voltage, as needed, to move electric power through the transmission system.[15]

Substations generally contain a variety of equipment, including transformers, switches, relays, circuit breakers, and system operations instruments and controls.[16] Transformers are the critical electrical component that facilitates the efficient transfer of electric power by converting electric power to different voltages along the delivery system (see fig. 3).[17] Large power transformers consist of two main active internal parts—the core, which is made of magnetic material such as layered steel, and windings, which are coils of wire wound around the core to change voltage and

[13]The federal hydroelectric power plants are owned and operated by the U.S. Army Corps of Engineers, the Bureau of Reclamation in the Department of the Interior, or the International Boundary and Water Commission. In addition, the Tennessee Valley Authority—a federal government corporation—generates, sells, and transmits electric power in seven states.

[14]Section 215 of the Federal Power Act (*codified at* 16 U.S.C. § 824o) requires the Electric Reliability Organization to develop mandatory and enforceable reliability standards, which are subject to FERC review and approval. FERC-approved reliability standards become mandatory and enforceable in the U.S. on a date established in the Orders approving the standards.

[15]Standard AC transmission voltages in the United States are 69, 115, 138, 161, 230, 345, 500, and 765 kilovolts. DOE classifies high-voltage transmission as those lines operating at or above 230 kilovolts.

[16]A relay is a switch, which sends a signal to connect or disconnect electric power equipment.

[17]Power transformers perform one of two tasks: (1) they are used to step up or "transform" the voltage of electric power produced at generators into high voltage for efficient transmission; and (2) they are used to step down or "transform" high transmission voltages to lower transmission or distribution voltages.

current levels. There are two sets of windings: the primary through which electric power flows into the transformer and the secondary windings through which electric power flows out of the transformer.

Figure 3: Large power transformer

Source: Department of Energy. | GAO-19-98

Transformers come in a wide variety of sizes and configurations. For instance, transformers are available that can step up voltages or step down voltages, as required. Transformers are also designed to operate at different levels of electric power. Because it is generally more efficient, electric power is transmitted in three components that change direction with time, called phases. Taken together, the three phases ideally deliver constant power. As seen in figure 4, in the high voltage transmission system, each of the three phases is carried on a separate electric conductor while smaller wires above protect against lightning damage.

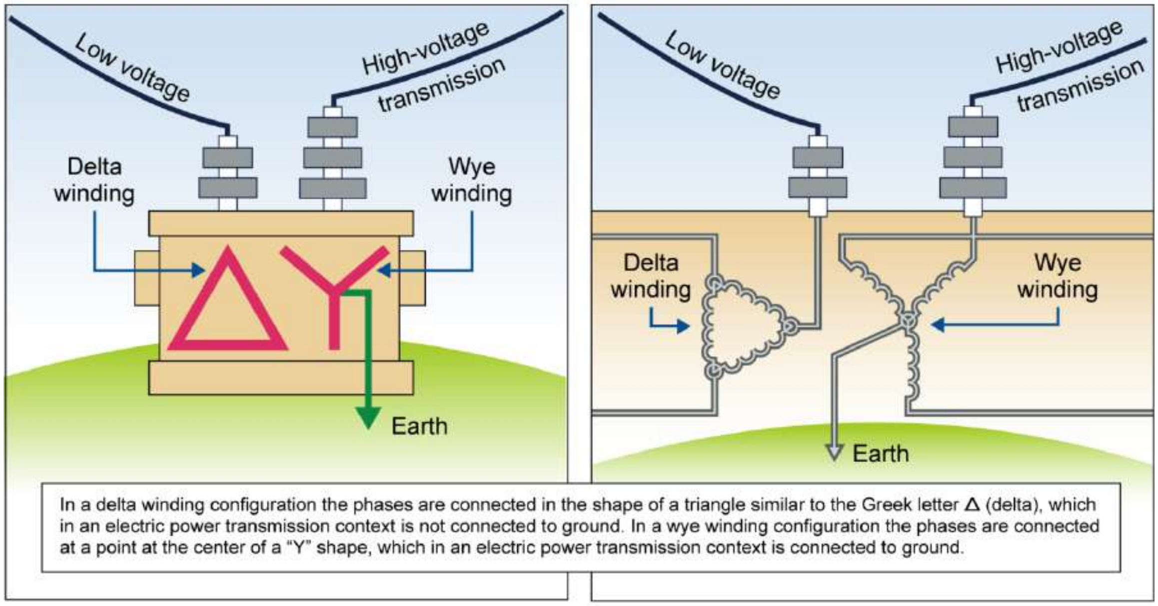
Consequently, transformers also must be able to handle three-phase electric power, which is accomplished with a single three-phase transformer with a common core or with a bank of three individual, single-phase transformers. For both the primary and secondary windings, there are two ways to connect the three phases: wye-connection and delta-connection. As seen in figure 5, in the wye configuration the phases are connected at a point at the center of a "Y" shape, the neutral connection, and in the electric power transmission context is connected to ground, and in the delta configuration the phases are connected in the shape of a triangle, similar to the Greek letter Δ (delta), and in the electric power transmission context is not connected to ground. Transformers connected to the transmission grid are usually wye-configured on the high-voltage, low-current sides and delta-configured on the low-voltage, high-current sides.

Figure 4: High-voltage transmission lines

Source: National Archives and Records Administration (Ansel Adams for the Department of the Interior, National Park Service) (1941).
GAO-19-98

One transformer manufacturer told us that depending on the function of the transformer, the voltage rating, and the model, the approximate cost of a large power transformer weighing from 170 to 410 tons ranged from $2 million to $7.5 million in 2017

Figure 5: **Illustration (left) and schematic (right) of delta-wound and wye-wound connections**



Source: GAO. | GAO-19-98

in the United States.[18]

In addition to transformers, substations contain a variety of equipment designed to help electric power suppliers ensure the reliable flow of electric power through the grid. For instance, switches are used to direct the flow of electric power over different lines and can also be used to isolate certain sections of the substation so maintenance can be conducted. Circuit breakers are used to disconnect parts of the system when faults, such as when too much current is present, are detected.

[18]The cost estimates apply to a large power transformer with a power rating between 300 megavolt-amperes and 750 megavolt-amperes. The cost estimates do not include transportation, installation, or other associated expenses, which DOE estimates generally add 25 to 30 percent to the total cost of a transformer. Transformer labor costs and material prices vary by manufacturer, market condition, and by location of the manufacturing facility.

Power flow through an electric power system has two components: usable power and reactive power. Usable power is often called active power or real power; it can do work, such as turn motors and produce light. Reactive power flows continuously back and forth between magnetic and electric fields in the electric power system; it is not available to electric power consumers to do work. Reactive power can limit usable power flow and affect the voltage stability of the electric grid—that is, the ability of the electric grid to accommodate changes in power consumption. Certain types of grid equipment can compensate for reactive power flow. For example, power flow in series capacitors can be used to compensate for reactive power flow in the inductance of long transmission lines. Capacitors and inductors housed at substations can also be used to compensate for reactive power flow. Generators must have additional capacity in order to compensate for power diverted to reactive power in addition to supplying usable power required by customers.

1.3 Geomagnetic disturbances are caused by space weather

Space weather refers to the changing conditions of the interplanetary environment that arise from solar activity. Solar cycles comprise periods of waxing and waning solar activity that are characterized by the number of sunspots. The most significant types of space weather that affect the electric grid are solar wind and coronal mass ejections (CME) that emit radiation and particles that can travel toward and interact with Earth.[19] The solar wind is a magnetically-active flow of energetic charged particles referred to as plasma. The solar wind continuously streams radially outward from the sun and its flow shapes Earth's magnetic field. During a geomagnetic storm, CMEs produce significantly more charged particles, or plasma, often traveling toward earth at a higher rate of speed than the background solar wind, which can affect the electric grid. CMEs are often, but not always, associated with solar flares.

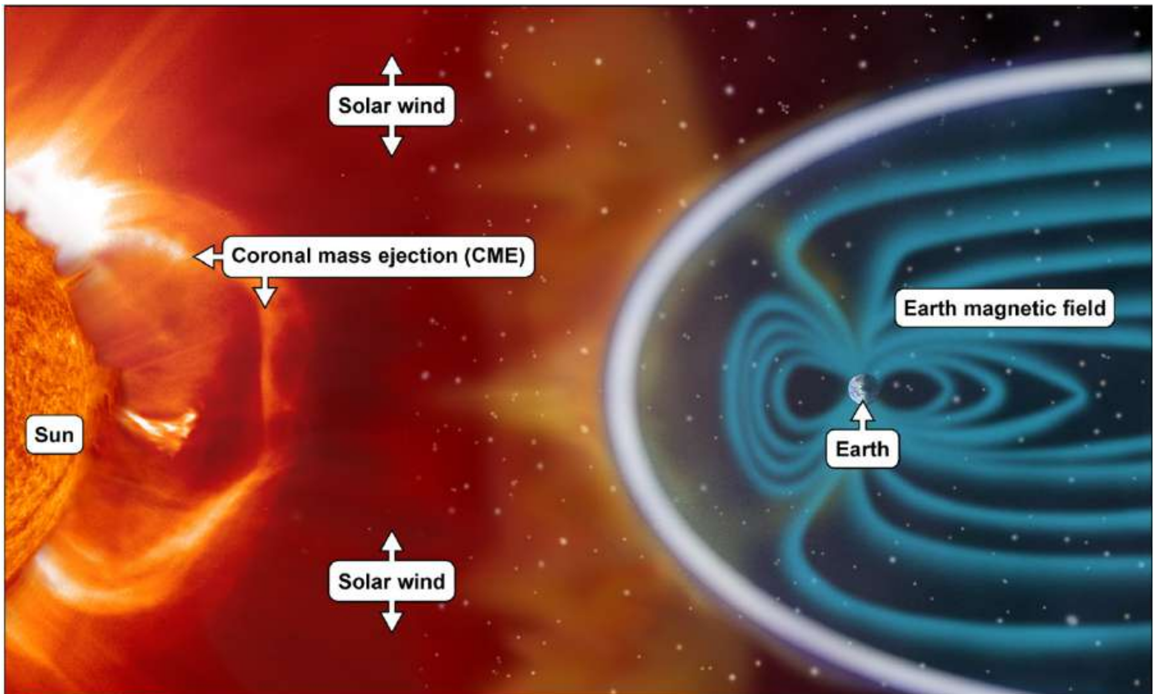
The CMEs interact with Earth's upper atmosphere and disturb Earth's magnetic field, which is shaped by the background solar wind. Within the upper atmosphere, interactions with solar radiation form an ionized, electrically conductive region known as the ionosphere. Earth's magnetic field extends beyond its atmosphere. Figure 6 depicts the region of space where Earth's magnetic field remains dominant, called the magnetosphere. During geomagnetic storms, CMEs can drive electric currents in the ionosphere and magnetosphere. Geomagnetic storms usually last about a day. Substorms—periods of intense activity lasting 1 to 3 hours each—can constitute GMDs of sufficient magnitude to affect the power grid.

Several federal agencies, primarily NOAA, NASA, and USGS, provide operational and research resources to forecast, model, and understand space weather and its effects, including on the electric grid. In addition to observational monitoring, NASA and NOAA provide modeling, analysis, and interpretation of data on the sun and the interconnected system linking the sun to Earth. NASA and NOAA researchers work in an interdisciplinary community to address aspects of science that affect life and society, including GMD. For instance, in August 2018, NASA launched the Parker Solar Probe, which will travel to the sun's atmosphere to collect measurements to improve our understanding of the sun's corona and the origin and evolution of solar wind. USGS collaborates with the other agencies on geomagnetic products, modeling, and research. Of greatest relevance to electric utilities, USGS operates magnetic observatories that monitor geomagnetic field, provides maps of the electrical resistivity of Earth, and develops models to calculate the geoelectric field.

NASA and NOAA operate four satellites approximately 1 million miles from Earth toward the sun to provide observations of solar activity. The NOAA Deep Space Climate

[19]Solar flares and coronal holes are other types of solar activity that do not cause significant effects on the electric grid. Solar flares are sudden, bright emissions from regions of sunspot activity. Visible light is a prominent form of electromagnetic radiation emanating from the Sun. Solar flares emit a broad spectrum of solar electromagnetic radiation (from radio frequencies to x-rays) as well as energetic charged particles. Coronal holes emit high-speed particle flows that also contribute to the solar wind.

Figure 6: Coronal mass ejection (CME) approaching Earth



CMEs emit particles that can travel toward and interact with Earth's upper atmosphere and disturb its magnetic field, which is shaped by the background solar wind.

Source: National Aeronautics and Space Administration (illustration). | GAO-19-98

Observatory (DSCOVR) satellite provides real-time operational monitoring of space weather. NASA's older Advanced Composition Explorer (ACE) and Wind satellites continue to provide space weather data. The European Space Agency and NASA's joint Solar and Heliospheric Observatory (SOHO) satellite provides research data. USGS operates 14 ground-based magnetic observatories located across the United States to measure the local magnetic field using carefully calibrated magnetometers. These magnetic observatories can detect when GMDs are affecting Earth's magnetic fields at those locations.[20] USGS shares its data through the International Real-time Magnetic Observatory Network (INTERMAGNET), an international consortium of geophysical institutes.

NOAA SWPC forecasts and monitors space weather using data from NOAA, NASA, USGS, the Department of Defense, and international observatories. For significant space weather events, SWPC issues bulletins in the form of watches, warnings, and alerts. The longest lead time bulletins—watches—are typically

[20]Variometers are also used by some organizations to detect GMDs on Earth. Variometers are lower-cost instruments to own and operate for those concerned with GMD effects because they are not calibrated to absolute magnetic field and instead measure the rate of change in magnetic field.

issued 48 hours in advance of a predicted geomagnetic storm that may cause power grid fluctuations.[21] Warnings are posted after the CME passes the NOAA DSCOVR satellite, about 40 minutes in advance of an approaching geomagnetic storm that may cause power grid fluctuations.[22] Alerts are near real-time indications that a geomagnetic storm is occurring. SWPC has established a space weather scale that corresponds in a straightforward way to the effects of geomagnetic storms. This scale is based on a planetary average of irregular fluctuations in the geomagnetic field. Consequently, SWPC's bulletins provide information on a planetary scale, meaning that there could be significant geomagnetic effects somewhere on Earth. To improve the usefulness of its bulletins in the United States, SWPC utilizes its geospace model, which provides short-term predictions of regional geomagnetic disturbances, and is developing a model of local effects of GMDs called the Geoelectric Field Map, which reports the geoelectric hazard across the contiguous United States. It was released experimentally in October 2017.

1.4 GMDs can cause geomagnetically induced currents in transmission lines

Electric currents flow within space, the upper atmosphere, and in the ground. Within Earth's upper atmosphere, the ionosphere conducts electricity. Currents flowing within the ground and oceans are referred to as telluric—meaning earth—current. They are driven by variations in the geomagnetic field or the motion of seawater across the earth's magnetic field.

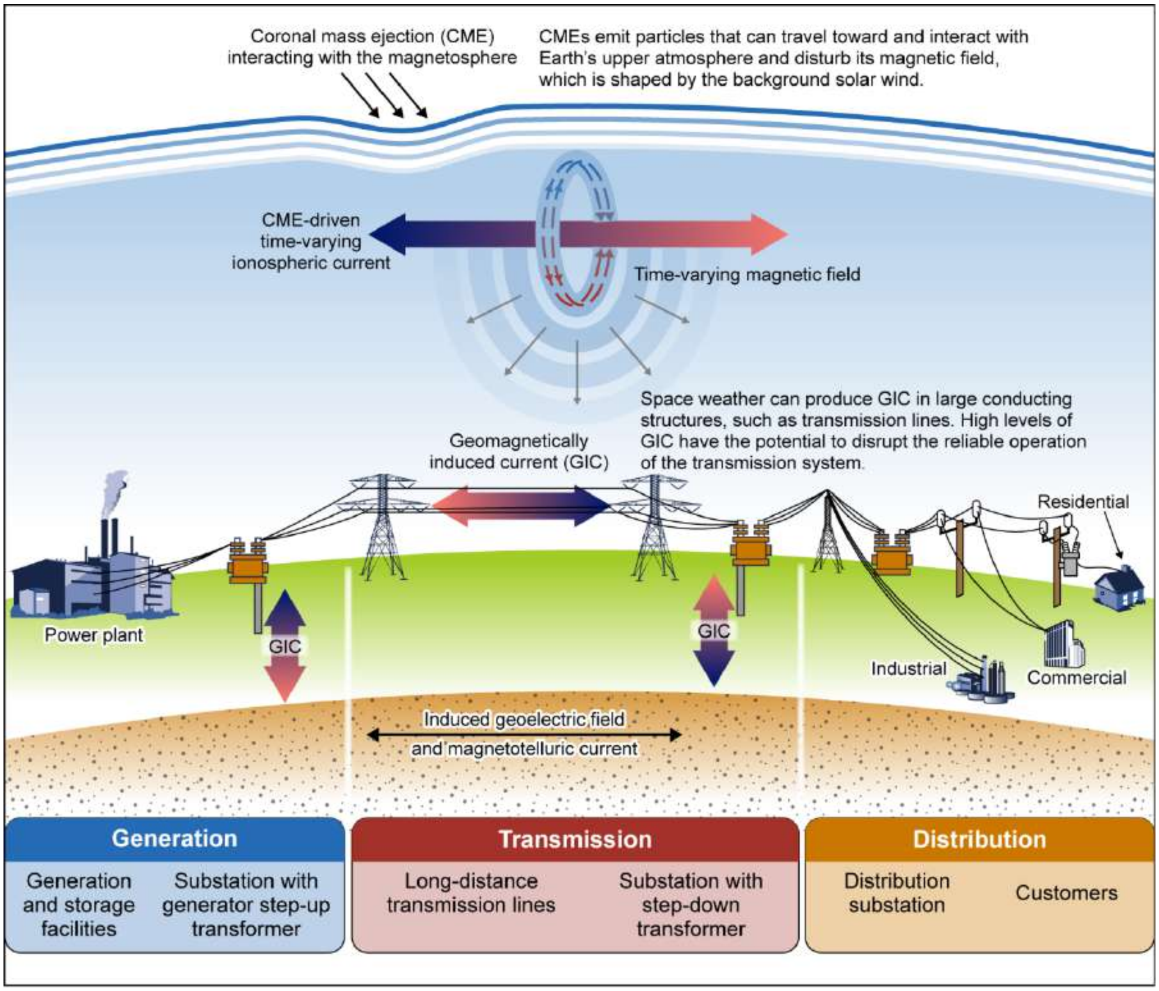
Space weather drives the flow of electric current in Earth's ionosphere and magnetosphere. Two of these current systems in the ionosphere are near the northern and southern magnetic poles and are known as the auroral electrojets. The auroral electrojets flow approximately 60 miles above Earth spread over approximately 5 degrees of latitude. The electrojets and other ionospheric and magnetospheric currents induce electric currents within Earth; taken together, these currents determine a time-varying geomagnetic field at Earth's surface.

The geoelectric field at Earth's surface drives electric currents. It is determined by the intensity of the GMD, which is based on changes in Earth's magnetic field and the resistivity of Earth, which is based on geology and varies with depth and location. These geoelectric fields can drive geomagnetically induced current (GIC) in large conducting structures, such as transmission lines (see fig. 7). GMDs vary at a low frequency that is significantly slower than the variation in the electric supply voltage. By North American convention, the grid has an alternating current, which oscillates at a frequency of 60 cycles per second. GIC varies approximately 60 to 6 million times more slowly and may be approximated as a constant or DC. High levels of GIC have the potential to disrupt the reliable operation of the transmission system, as discussed below.

[21] The lead-time could be longer or shorter based on the speed of the storm. The fastest-moving storm on record arrived at the Earth from the Sun in less than 15 hours; it takes SWPC up to 3 hours to receive the remote observations and model the data before issuing a watch.

[22] During a recent extreme storm in October 2003, the GMD arrived at Earth about 14 minutes after the storm passed the spacecraft used to inform a warning.

Figure 7: Coronal mass ejections cause geomagnetic disturbances that may interact with the electric power grid



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

2 Large Geomagnetic Disturbances Could Affect the Reliable Operation of the U.S. Electric Grid, but the Magnitude of Potential Damages Is Not Fully Understood

Although GMDs occur regularly, they have rarely caused damage to electric grid equipment or caused large-scale service outages. Historically, only large GMDs—those defined by NOAA as severe or extreme—have led to such damage. However, the magnitude of potential damages from a large GMD is not fully understood, in part, because there have been few examples worldwide of GMDs that have caused equipment damage or large-scale blackouts. Determining how GMDs will interact with and harm the electric grid is challenging because the magnitude of the ensuing GIC is influenced by several factors. The reaction of specific components of the electric grid to GIC and its secondary effects is also challenging to accurately model.

2.1 Geomagnetic disturbances occur regularly, but have rarely caused electric grid damage or service outages

Geomagnetic storms occur regularly as a result of space weather. NOAA SWPC has established a geomagnetic storm scale (referred to as the “G” scale) to classify the potential effects and intensity of a GMD as recorded by the planetary K-index, a measure of GMD intensity (see table 1).[23] The majority of geomagnetic activity does not rise to storm levels and is classified as G0 activity.

Solar activity—including CMEs—is commonly tracked across solar cycles.[24] According to SWPC, there are approximately 130 days with G1–G5 geomagnetic storms in an average year of a solar cycle, but only severe and extreme storms (G4 and G5) are associated with potential widespread, significant electric grid problems. As seen in figure 8, minor (G1) geomagnetic storms are common in the 85 years since 1933 and the beginning of solar cycle 17—the first complete solar cycle within the consistent historical record of GMD intensity. In contrast, there have been 22 extreme (G5) geomagnetic storms over the same period. There are variations in the level of solar activity in each solar cycle and the current solar cycle, 24, has been particularly quiet. However, an extreme geomagnetic event can occur at any time.

In rare instances, CMEs are of such intensity and orientation as to cause a large GMD that could significantly affect the grid by damaging critical electric grid equipment, such as a transformer, or causing a large-scale service interruption. Since 1932, we found only four geomagnetic storms—two extreme (G5)

[23] The metric for SWPC alerts is its minute-by-minute estimate of a planetary-scale measure of the intensity of GMDs known as the K_p-index. The official K_p-index records global GMDs continually, eight times per day since 1932. It is a weighted average of irregular fluctuations as measured at thirteen magnetic observatories spanning as far south as New Zealand through as far north as Scotland.

[24] Solar activity levels (e.g., frequency of solar flares and CMEs) and appearance (primarily the number of sunspots, or dark, low temperature areas on the surface of the Sun caused by magnetic activity) follow the broad trend of waxing and waning over a period of about 11 years referred to as solar cycles. As of June 2018, solar cycle 24 is ongoing and in its 10th year.

Table 1: National Oceanic and Atmospheric Administration geomagnetic storm scale and potential effects

Geomagnetic storm scale	Corresponding physical measure	Description	Potential effect on the power grid
G0	K_p = 0–4⅓	Below storm levels	No significant effect.
G1	K_p = 4⅔–5⅓	Minor	Weak fluctuations may occur.
G2	K_p = 5⅔–6⅓	Moderate	Voltage fluctuations may affect high-latitude power systems.
G3	K_p = 6⅔–7⅓	Strong	Voltage corrections may be required; false alarms triggered on some protection devices.
G4	K_p = 7⅔–8⅔	Severe	Possible widespread voltage control problems and some protective systems may mistakenly disconnect key assets from the grid.
G5	K_p = 9	Extreme	Widespread voltage control problems and protective system problems can occur; some grid systems may experience blackout. Some transformers may experience damage.

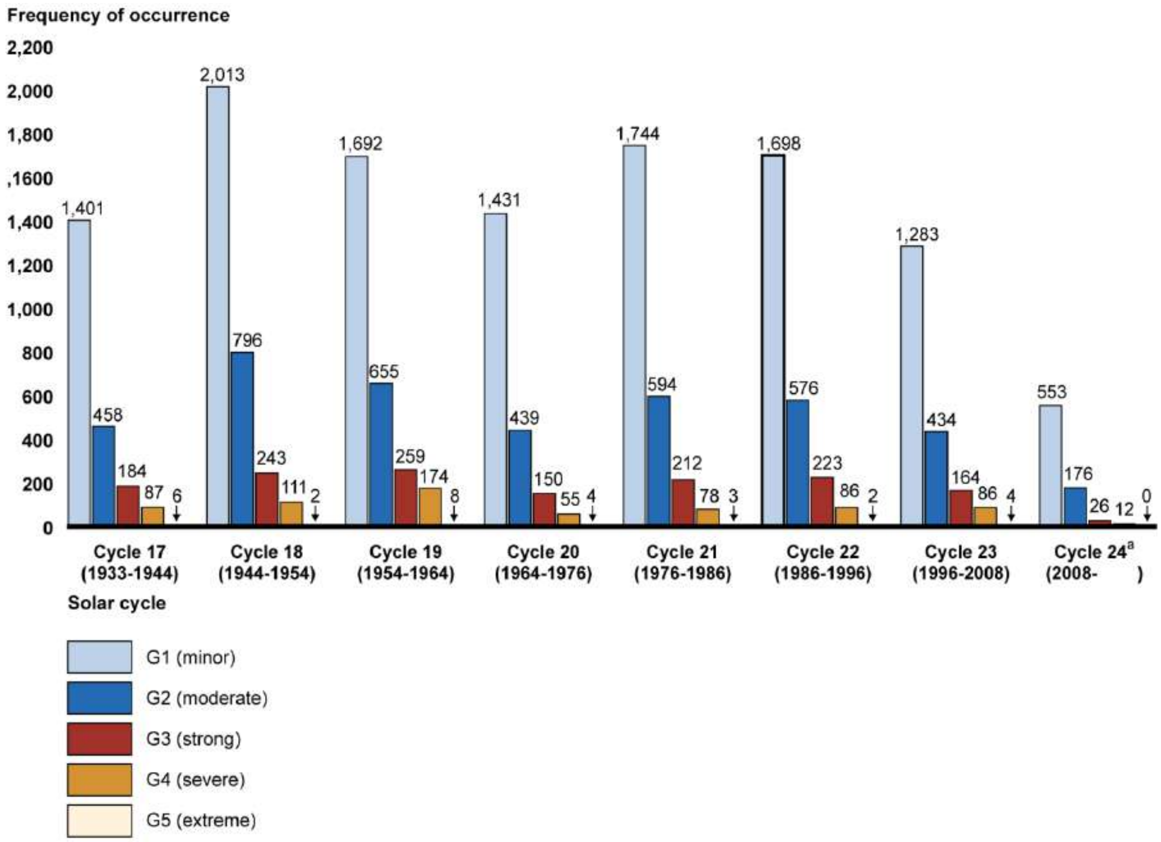
Source: GAO summary of National Oceanic and Atmospheric Administration Space Weather Prediction Center information. | GAO-19-98

Note: The Planetary K-index (denoted K_p-index) is based on measurements from 13 global magnetic observatories.

storms, in March 1989 and October 2003, and two severe (G4) storms, in September 1989 and November 2001—have led to large-scale electrical service interruptions or damaged transformers anywhere in the world.[25] In none of these cases was a large-scale service interruption caused by a transformer damaged by GMD. Further, in the United States, the only significant effect of geomagnetic storms on the electric grid has been thermal damage to four single-phase transformers resulting from GMDs in March and September 1989; we found no reported electrical service interruptions resulting from GMDs. Other extreme (G5) and severe (G4) geomagnetic storms caused effects on the electric grid in the United States that were noticed by electric power suppliers, but effects were often limited to protective relay misoperation and did not result in

[25]The NOAA geomagnetic storm index is a range index—a measure of variation that tops out at G5. There can be significant variation in GMD intensity among extreme (G5) geomagnetic storms. For example, according to a NOAA official, the 1989 storm was twice the intensity of the 2003 storm.

Figure 8: Planetary geomagnetic disturbance (GMD) intensity by solar cycle, 1933–2017



Source: GAO analysis of GFZ German Centre for Geosciences data. | GAO-19-98

Note: Readings are averaged and reported over 3-hour intervals and grouped according to solar cycle, which is a period of solar activity that reflects changes in the sun's activity levels (e.g., levels of solar wind and coronal mass ejections) and appearance (primarily changes in the number of sunspots—dark, low temperature regions on the surface of the sun caused by magnetic activity) about every 11 years. A single geomagnetic storm may encompass more than one 3-hour interval; for example, the 29 extreme (G5) records shown constituted 22 geomagnetic storms.

[a] Solar cycle 24 is ongoing and in its 10th year as of December 31, 2017.

damage to critical electric grid equipment or a service interruption.[26]

The four geomagnetic storms mentioned above had more significant effects on other countries' electric grids. The most recent extreme (G5) geomagnetic storm that had a significant effect on an electric grid occurred in October 2003. Transformers in southern Sweden saturated and caused protective relay misoperation, resulting in a power interruption that lasted up to 50 minutes and affected about 50,000 customers.[27] This

[26]Protective relay misoperation is the incorrect or undesired operation of protective relays, that is, protective relays triggering switches to unintentionally connect or disconnect equipment when it should not or failing to operate when it should.

[27]A transformer saturates after its core is fully magnetized. This saturation can produce severe disturbances in the grid voltage. GIC can drive power transformers into saturation,

power interruption affected a limited service area and no equipment damage was reported. This storm is also suspected of contributing to thermal damage to as many as 15 transformers in South Africa and Namibia, which share a network. In these southern African cases, the thermal damage was discovered more than 2 weeks after the GMD and no power interruptions were reported. In November 2001, a single-phase transformer in New Zealand failed during a severe (G4) geomagnetic storm, but was replaced within hours with a spare transformer.

In March 1989, an extreme (G5) geomagnetic storm resulted in the only large-scale blackout attributed to GMD. Transformers exposed to GIC-produced harmonics—distortions to ideal, smoothly varying, alternating currents—caused protective relay misoperation at the Canadian provincial utility Hydro-Québec. Within 92 seconds, voltage instabilities resulted in a system-wide blackout that affected about 6 million customers. Service was restored to half of the affected customers in about 7 hours and to most customers in 9 hours. As the blackout occurred, three transformers were damaged by overvoltage conditions.

which is the source of virtually all GMD-induced issues in electric power transmission. Magnetic materials, such as those used in power transformer cores, are collections of magnets called domains. Placing magnetic material in a magnetic field, such as in the windings of a transformer, aligns its domains in the direction of the field. As the magnetic field is increased, more domains are aligned, themselves adding to produce a magnetic field. When nearly all of the domains are aligned, this condition is called saturation. GIC adds a direct current offset to current flowing into transformers; this can drive transformers into magnetic saturation during the half-cycle for which transformer input current adds constructively to GIC.

In this incident, the GMD drove GIC, which caused the transformers to saturate.[28] These saturated transformers injected harmonics into the Hydro-Québec grid, which caused equipment designed to compensate for reactive power flow to disconnect from the grid at three substations. The saturated transformers also experienced elevated reactive power flow, which the equipment otherwise might have provided. As a result, the grid voltage became unstable. The grid frequency decreased rapidly over 8 seconds, causing protective relays to disconnect five high-voltage transmission lines between generating stations in northern Quebec, including a hydroelectric complex, and populous regions in southern Quebec. Following this disconnection of transmission lines, hydroelectric generating stations experienced a rapid loss of load, which caused the voltage to suddenly increase and damage two single-phase generator step-up transformers.[29] A third single-phase transformer was damaged that was attached to substation equipment designed to compensate for reactive power flow. Meanwhile, the rest of the grid experienced a rapid loss of generation. As automatic systems failed to compensate, two other

[28] The blackout was not caused by the onset of the geomagnetic storm, but rather by the third in a series of substorms separated by approximately 1–2 hours. The Hydro-Québec grid was first impacted by the second substorm, although operators were able to respond. The third substorm caused the system-wide blackout. The fourth substorm, which occurred during the blackout and thus did not further damage the grid, was the largest GMD, as recorded by the geomagnetic observatory in Ottawa.

[29] Generator step-up transformers are used to convert power produced by power plants into high voltages needed to transmit power over long-distance transmission systems. According to DHS and the NERC GMD Task Force, generator step-up transformers usually operate near full load and could be particularly vulnerable to GIC.

hydroelectric generation complexes disconnected from the grid, resulting in a system-wide blackout.

In addition to damaging the Hydro-Québec electrical system, the March 1989 storm damaged electrical equipment in the United Kingdom and the United States. In the United Kingdom, two high-voltage transformers were thermally damaged during the storm. In the United States, the Salem nuclear plant operator in New Jersey discovered thermal damage to all three phases of a generator step-up transformer when testing the transformer oil a week later. An identical single-phase generator step-up transformer at the Salem nuclear plant was found thermally damaged during testing 3 days after a severe (G4) storm in September 1989. None of these transformer failures resulted in a service interruption.

In the mid-20th century, there were sporadic reports of extreme (G5) GMDs affecting the electric grid. The earliest reported instance of GMD effects on the U. S. electric grid was in March 1940.[30] However, neither service interruptions nor serious operating difficulties were reported. In February 1958, GMD caused a small-scale, 4-minute interruption in Ontario, Canada. In August 1972, U.S. and Canadian utilities observed large GIC and large-scale effects on system stability, but reported neither service outages nor transformer damage.

Reports of the effects of significant GMDs that predated the modern, interconnected electric grid were largely related to communication systems, such as the telegraph. Three incidents probably would have significantly impacted the electric grid had it existed at those times. The very first recorded geomagnetic disruptions of any manmade system—the telegraph—occurred in the 1840s with the observation of "spontaneous electrical currents."[31] The second noteworthy GMD incident, in 1859, is referred to as the Carrington event, named after the amateur astronomer who made this first observation of a white-light solar flare associated with a CME. This GMD disrupted telegraph systems worldwide. Though there is no accurate measurement of this GMD, many experts believe that this event may represent the largest recorded GMD. The third noteworthy incident occurred in 1921 and disrupted communication systems in the United States and Europe. The 1921 storm was a large storm with GMD estimated to be similar to the Carrington event. These latter two events have been described as GMD events so severe that, on average, they have a probability of occurring once every 100 years.

2.2 The level of risk posed by geomagnetic disturbances to the U.S. electric grid is not fully understood

Several organizations have studied the level of risk posed by GMDs to the U.S. electric grid. However, there is some disagreement among the studies about the level of risk and the scale and extent of potential

[30] Davidson, W.F., "Sun-Spot Disturbances of Terrestrial Magnetism," *Electrical Engineering*, vol. 60, no. 2 (1941).

[31] Barlow, W.H., "On the Spontaneous Electrical Currents Observed in Wires of the Electric Telegraph," *Phil. Trans. Roy. Soc. London*, vol. 139 (1849). Recent scholarship suggests that geomagnetic effects were recorded during the first commercial uses of the telegraph in 1841: Cade, W.B., III, "The First Recorded Space Weather Impact?," *Space Weather*, vol. 11 (2013).

consequences that could result. The varying conclusions are, in part, a function of the numerous factors that influence how geomagnetic disturbances are caused, the magnitude of GIC that could be generated, and the amount of damage that could result. While much is known about these factors, there are key gaps in the understanding of these factors that limit the ability to understand, monitor, and assess the risks posed by GMD on the U.S. electric grid.

2.2.1 Electric grid effects from GMDs are influenced by several factors

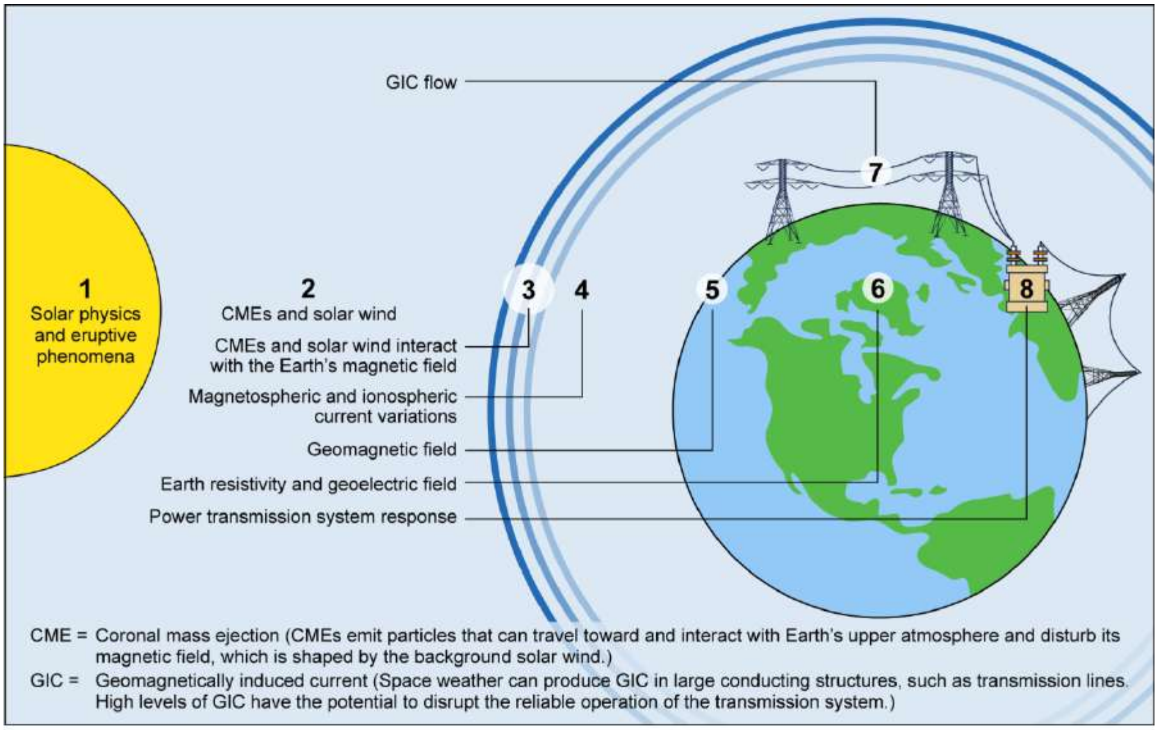
Because the phenomena that lead to GMDs and GIC and their effects begin with activity on the sun and extends to the design and operation of the electric grid, understanding it spans domains of scientific and engineering expertise, including solar physics, geophysics, electromagnetic physics, and electrical and mechanical engineering. Consequently, there are numerous factors that influence how GMDs may affect the electric grid. Researchers have grouped these various factors into eight stages, from CME formation through GMD effects on the electric grid, as illustrated in figure 9.

- The first two stages (1–2) relate to solar physics and CMEs and the solar wind.
- The next two stages (3–4) relate to the interaction between the CMEs and Earth's magnetic field and upper atmosphere.
- The fifth and sixth stages (5–6) comprise the resulting changes in the geomagnetic field at Earth's surface, which interacts with local geology to induce a geoelectric field that drives GIC.
- The last two stages focus on the electric grid, specifically: (7) the GIC flow that results from the geoelectric field and properties of the electric grid, and (8) the system response of the electric grid in the presence of GIC of sufficient amplitude to saturate transformers.

Space weather is created by the sun and may propagate toward Earth (stages 1 and 2)

Space weather, particularly CMEs, and the resulting GMDs drive GIC. According to NASA and NOAA officials, CMEs are the only type of space weather that can cause a large enough GMD to significantly affect the electric grid. The intensity of a GMD is influenced by the characteristics of a CME, including its mass distribution, speed, and—importantly—the orientation of its internal magnetic field relative to Earth's magnetic field. The intensity of a GMD is also determined by other factors, including the trajectory of the CME with respect to the path between the sun and Earth: whether it directly strikes Earth, interacts glancingly with the magnetosphere, or misses Earth. Earth-based observatories and satellites remotely sense solar activity; some of the satellite instruments image the sun's atmosphere while others monitor the passing solar wind.

Figure 9: Eight stages of factors affect geomagnetic storm impact on the electric grid



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

Space weather interacts with Earth's magnetic field and upper atmosphere (stages 3 and 4)

Geomagnetic storms can disturb Earth's magnetic field and generate electric currents in the magnetosphere and ionosphere. Geomagnetic latitude contributes to the intensity of GMDs with stronger and more frequent effects generally observed at higher geomagnetic latitudes.[32] When a CME interacts with Earth's magnetosphere, it energizes the magnetosphere on the far side of Earth, which then accelerates particles back toward Earth. These particles are typically constrained to follow Earth's magnetic field toward the poles. However, during intense geomagnetic storms, the magnetic field exposes lower geomagnetic latitudes, including the contiguous United States, potentially disrupting systems in more populous regions. As large geomagnetic storms could last on the order of a day, the rotation of Earth can move all of its regions underneath the areas of largest GMD. GMD-induced variations in the electric currents in the magnetosphere and ionosphere are challenging to measure or calculate at global scale while capturing highly localized enhancements. A satellite research mission—the National Science Foundation-funded Active Magnetosphere and Planetary Electrodynamics Response Experiment—provides the only direct measurement of relevant ionospheric currents.

[32] Geomagnetic latitude is closely related to geographic latitude, with the former determined by Earth's present magnetic field configuration; the geomagnetic poles are offset by several degrees from the geographic poles.

GMD produces a geoelectric field on the surface of Earth (stages 5 and 6)

Variations in the electric current systems in Earth's magnetosphere and ionosphere interact with local geology to affect the geomagnetic field. Fluctuations in geomagnetic field over time and spatial variations in the geomagnetic field and Earth resistivity produce a geoelectric field that drives GIC. The frequency of the geomagnetic field determines the depth within Earth to which the geomagnetic field penetrates to produce the geoelectric field. Earth resistivity is the complex electromagnetic response of geography and geology—from the surface through hundreds of miles deep—that relates variations in the geomagnetic field to the geoelectric field at the surface. The larger the Earth resistivity, the larger the geoelectric field at the surface and, other things being equal, the larger the resulting GIC. According to the NASA Living With a Star Institute GIC Working Group, an interdisciplinary team of researchers, the geoelectric field is the key product of scientific studies for use as the physical quantity driving GIC in engineering studies of the electric grid.

Predictive modeling of GMD intensity—variation over time of the geomagnetic field at Earth's surface—remains an area of uncertainty. Modeling these electric current variations and resulting geomagnetic field variation are areas of significant recent progress. NOAA SWPC models global geomagnetic conditions based on known solar wind conditions using the Space Weather Modeling Framework. In addition to the challenges of understanding how GMD events can impact manmade systems, researchers also question their ability to predict the likelihood and intensity of extreme events.

Because extreme GMDs are rare, researchers have used statistics that capture the physics of moderate events to estimate extreme events. However, scientists indicate that more intense GMDs can occur at lower geomagnetic latitudes. Therefore, researchers at Los Alamos National Laboratory found that the probability of extreme events is not accurately described by statistical models of historical records.[33]

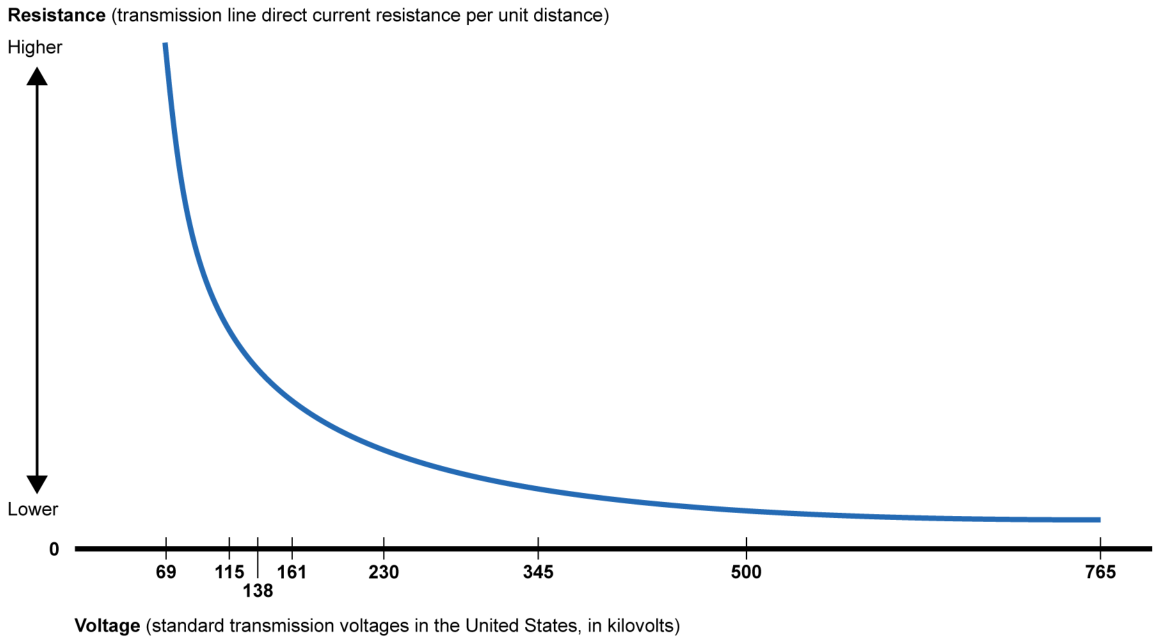
Geoelectric fields can drive GIC in the transmission system (stage 7)

The amount of GIC flow in the power system depends on the magnitude and orientation of the geoelectric field and the characteristics of the electric grid, including the type, length, and orientation of transmission lines. Because GIC can be approximated as DC, the DC resistance of transmission lines, transformers, and substation ground impact the level of GIC.

Trends in the U.S. electric power industry have been toward increased voltage and length of transmission lines that can increase their susceptibility to GIC. The electric grid—including transmission lines, transformers, and substation ground—is designed for low resistance to reduce transmission losses. As the voltage of transmission lines increases, their effective DC resistance tends to decrease, as shown in figure 10, through use

[33]Los Alamos National Laboratory is a Federally Funded Research and Development Center executing work in all of DOE's missions: national security, science, energy, and environmental management. Los Alamos performs work for DOE, DHS, the Department of Defense, and the Intelligence Community, among others on topics including nuclear security, intelligence, defense, emergency response, nonproliferation, counterterrorism, energy security, emerging threats, and environmental management.

Figure 10: Effective transmission line direct current (DC) resistance decreases with voltage



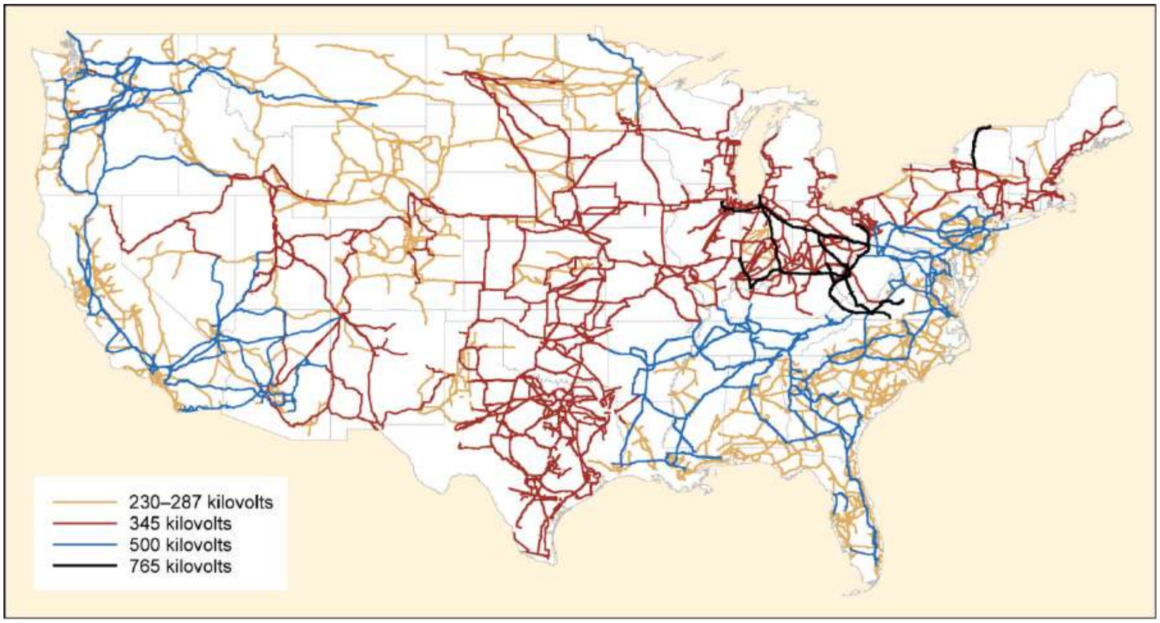
Source: GAO analysis of POWERSYS Solutions data. | GAO-19-98

of wires with larger effective diameter.[34] While these designs offer benefits for transmitting electric power under normal circumstances, the lower the resistance of a transmission line and its circuit, the higher the GIC can be during a GMD.

Utilities have constructed transmission lines over increasingly long distance to reliably connect large-scale generators to customers. GIC increases with transmission line length up to a point. For lines with relatively short distances between substations, the resistance of the transformer and substation ground primarily determine GIC. In contrast, for transmission lines with very long distances between substations, the transmission lines are the primary contributor to DC resistance. Over such long distances, GIC is insensitive to the resistance of the transformer windings and substation ground and approaches a limit determined by the geoelectric field and the transmission line design. The total length of transmission infrastructure at and above 100 kilovolts in the United States has increased 25-fold over the past 85 years. Most transmission lines remain in the high-voltage range of 230–345 kilovolts with some of the longest lines at higher voltages, as depicted in figure 11. The increased length and decreased effective resistance of transmission lines increases GIC. For instance, the transmission voltage and line length contributed to the Hydro-Québec blackout in 1989. Hydro-Québec’s transmission network transfers power at 735 kilovolts using over 7,000 miles of transmission lines from large, northern hydroelectric power plants to the metropolitan areas of southern Quebec.

[34]Using higher voltage transmission lines can reduce resistive losses, increase power flows, improve stability, and may improve the overall economics of the transmission line. Power is the product of voltage and current at any instant; for example, other things being equal, doubling input voltage halves input current and reduces resistive losses by 75 percent.

Figure 11: High-voltage electric transmission lines in the contiguous United States by voltage class



Source: GAO analysis of Department of Homeland Security data. | GAO-19-98

Note: The volt is the international system of units name for the electromotive force that causes electric power to flow through a conductor, with a kilovolt representing 1,000 volts.

Further, four factors may contribute to localized enhancement of GIC, which increase its impact: localized variation in the geomagnetic field, geology, geography, and grid topology. First, localized enhancement of GIC is related to spatial variation in the geomagnetic field. Second, the spatial variation in Earth resistivity due to geological variations can create areas of relatively high field. Third, abrupt changes in geography may act to concentrate currents, for example, near the sea coast. This phenomenon is referred to as the "coast effect", where proximity to saltwater bodies may increase GIC. Fourth, substations isolated at the edges of transmission networks can experience elevated GIC where the current flow is confined to one direction rather than distributed through a network.

GIC can affect the electric transmission system (stage 8)

The disruption or damage GMDs can cause on the grid is the result of GIC in transformers. GIC of sufficient magnitude and duration will saturate transformers, which causes three primary effects:

1. **Harmonics** are generated and propagate into the grid, where their effects on grid equipment can result in power interruption or equipment damage. When transformers saturate, current into transformers is distorted.[35] Such distorted currents can cause protective relays to

[35] These current distortions are repetitive, based on the 60 cycles-per-second power frequency. The added components, called harmonics, are at frequencies which are multiples of the repetitive frequency.

misoperate, specifically, to connect or disconnect other grid components when they should not. System operators receive ambiguous feedback as to whether the protective relay operation was due to GIC or actual malfunction. Harmonics also can physically stress electric grid equipment, including the heating and potential failure of generators and capacitors. Both of these effects can interfere with power flow in the grid, resulting in power interruption or equipment damage, such as during the March 1989 and October 2003 GMDs.

2. **Increased reactive power flow** reduces the efficiency and stability of the power transmission system. When transformers saturate, they require additional reactive power. If generators cannot supply additional power to compensate for this increased reactive power flow, usable power will be reduced and, if other methods are not available to compensate for this increase, the grid voltage can drop. Such instability may cause protective equipment to disconnect parts of the grid, which could result in power interruption or even large-scale blackout. For example, the Northeast United States blackout of 2003 was initiated by loss of transmission capacity followed by voltage drop and blackout. Although not related to GMD, this event demonstrates the potential impact and scale of voltage instability.
3. **Increased transformer heating**, which may damage transformer components. When transformers saturate, magnetic fields extend, or "leak", out of their magnetic cores. These leaked magnetic fields can heat nearby transformer components made of magnetic materials and, in some transformer designs, can cause circulating currents to flow in transformer windings. Leaked magnetic fields and circulating currents can cause localized heating, which can damage insulating materials, evolve combustible gasses in transformer oil, and, if they cause large circulating currents, melt transformer windings. According to NERC officials, thermal damage is very rare and generally occurs in transformers of a certain design and transformers near the end of operational life. Yet several studies have considered the threat of simultaneous damage to many power transformers, leading to a prolonged power outage.

High-voltage transformers are more susceptible to saturation when exposed to GMD. Transformers connected to the electric transmission grid are typically wye-configured on the high-voltage side (as in figure 5) with an electrical "neutral" connection to Earth, which allows GIC to flow through the high-voltage transmission grid. Design variation throughout the electric grid presents some older, inherently vulnerable transformer designs. Investigations in New Jersey, Africa, and New Zealand suggested that the transformers that sustained damage during geomagnetic storms may have been more prone to failure. Certain transformer designs are less susceptible to GIC-related damage. For example, ABB and Hydro-Québec tested their 735 kilovolt transformer design with 75 amperes per phase of simulated GIC for 1 hour and concluded that thermal damage was not a major concern for this transformer design. In addition to transformers, protective relays have various designs that respond differently to harmonic currents. Protective relays that are digital can be programmed to reduce the likelihood of misoperation due to harmonics and therefore may be more resilient to the effects of GIC. A common GMD effect on the electric grid in the 20th century was the misoperation of protective relays that erroneously or undesirably disconnected transformers or capital equipment designed to compensate for reactive power flow. If generators cannot compensate for this situation, then voltage collapse and blackout could result.

2.2.2 Key studies lack consensus about the scale and likelihood of potential consequences of GMDs to the U.S. electric grid

Many electric power suppliers, reliability coordinators, national laboratories, insurers, electric power industry groups, and academics have studied aspects of the risk that GMD presents to the electric grid. However, they lack consensus on the expected scale and likelihood of potential consequences of GMDs to the U.S. electric grid. Earth experienced larger GMDs before the grid was fully constructed and it is not clear what effect such extreme events would have on the modern electric grid. A large GMD might have long-term, significant impacts on the nation's electric grid. Given the interdependency among infrastructure sectors, such a disruption to the electric grid could also result in potential cascading impacts on fuel distribution, transportation systems, food and water supplies, and communications and equipment for emergency services, as well as other communication systems that utilize electrical infrastructure. Recent reports by government and research organizations have questioned the long-term level of impact that a GMD could have on the electric grid and have recommended further research.

Several studies anticipate limited GIC-induced damage to transformers on the U.S. electric grid. A pair of national laboratories studies evaluated the impact of an extreme GMD event on the Eastern and Western Interconnections. Power flow simulations indicate that the disconnection or loss of transformers experiencing high GIC would avoid equipment damage and maintain grid stability. Assessments by national laboratories conclude it is possible to use operating procedures or GIC blocking technologies to protect transformers and grid stability during a GMD event. GIC tends to concentrate near the edge of the electric transmission grid, where generators and generator step-up transformers tend to be located. A detailed study of the secondary effects of GIC by an electric power supplier concluded that failures in generators or capacitors are unlikely during a 100-year storm.

Some organizations have raised a concern over a long-duration, large-scale blackout caused by GIC damaging electric grid equipment, namely transformers. However, subsequent studies question these conclusions. Separate studies by an insurer and a federal contractor raise the possibility of an extreme GMD event causing a long-duration, large-scale blackout—a "black sky" event—that affects tens of millions of people or more in the United States. An insurance industry working group has cautioned that a several-week power outage affecting urban areas would have catastrophic societal and economic impacts. The insurer's study, in particular, identifies between 20 and 40 million U.S. people at risk of blackout lasting between 16 days and 2 years. However, a Sandia National Laboratories review requested by FERC of the contractor report questioned the long-term level of impact GMD could have on the electric grid and recommended further research. A Los Alamos National Laboratory study identified limitations related to the contractor's study design. A study by JASON, an independent defense scientific advisory group, was also critical of such estimates stating that the authors were not convinced that the worst-case scenario was plausible. The NERC GMD Task Force concluded that the most likely worst-case system impacts from a severe GMD event would be voltage instability and potential blackout. Furthermore, blackouts that originate in the transmission grid in the absence of substantial equipment damage are generally restored within 3 days and often much sooner, according to Los Alamos National Laboratory and NERC.

In addition to the threat presented by an extreme GMD event, we identified three studies that suggested that low levels of GIC produced during less intense GMDs may also damage electric equipment. Two studies attributed transformer thermal damage to the cumulative effect of many small GIC events. A Zurich Insurance Group study identified that GMD is correlated with end-user insurance claims attributed to electrical issues.[36] According to federal researchers, this attribution remains inconclusive because a causal relationship has yet to be demonstrated.

[36]The authors speculated that this is due to the effects of GMD on power quality on the distribution grid; however, this study found no dependence on latitude. Generally speaking, stronger GMD effects would be expected at higher geomagnetic latitudes.

Several factors may contribute to the differing conclusions among studies that share fundamentally similar methodologies. While the factors that influence the potential damage to the grid are generally understood, in many cases the underlying assumptions, treatment of uncertainty, or depth of analysis differ.

Any study of GIC on the electric grid requires assumptions or engineering estimates. Assumptions and uncertainty within each of the factors limit the ability to accurately calculate the risk GMD poses to the U.S. electric grid. Notably, the research community lacks consensus over the likelihood and intensity of extreme GMDs used to define an extreme event in terms of geoelectric or, in some studies, geomagnetic field. The lack of frequent extreme events and limited historical records complicate setting an accurate benchmark. Discrepancies persist between physics-based models and statistical models of historical records. This contributes to the uncertainty around the likelihood and magnitude of the GMD threat. Studies of GIC that use the NERC benchmark GMD event description assume a geoelectric field for the input to stage 7. In 2016, FERC approved a NERC reliability standard on the planned performance of transmission systems during benchmark GMD events, which NERC defined as those with frequency of occurrence of approximately 1 in 100 years. However, a NERC standards drafting team is refining the standard to incorporate additional parameters of a 1-in-100 year GMD event, specifically to account for potentially localized enhancement of geomagnetic field in a severe GMD event in response to FERC direction.[37] Also, insurance companies operating in the European Union are required to plan for 1-in-200-year events, but lack an accepted benchmark GMD event description for such an event.

The factors in stages 1 to 6 are generally included in an assumption of a geomagnetic or geoelectric field due to limitations or uncertainty in scientific data. For example, some NASA researchers do not yet consider their modeling of solar physics mature enough to predict CME eruptions. Scientists have very limited capability to forecast GMD before the magnetic field of the CME is observed when passing by satellites. The location of monitoring satellites allows NOAA to revise forecasts and issue warnings up to about 40 minutes in advance of the GMD affecting Earth. JASON noted the importance of satellite-based observations and recommended additional operational satellites for monitoring space weather. NOAA SWPC forecasts periods of higher probability for geomagnetic storms and issues watches up to 3 days in advance, according to a NOAA official. Calculating the interaction between the solar wind and the magnetosphere requires models that are under development. Efforts are underway to model CME propagation from Sun to Earth, but observational data limits the accurate representation of CMEs required for predicting GIC.

Beyond the choice of assumptions when calculating the effects of an extreme GMD, researchers choose a depth of analysis to simulate the effects of GIC on transformer saturation and the electric grid. The response of the electric grid to GIC may be calculated to varying degrees of accuracy. According to grid software vendors, tools are commercially available and in development that will calculate GIC from the geoelectric field and DC characteristics of the grid. The first tier of estimating the impact of GIC involves assuming a GIC threshold value above which transformers may be at risk of thermal damage. The next tier of analysis is to simulate power flow in the electric grid with increased reactive power flow or when at-risk grid equipment is disconnected. This is the depth of analysis required by NERC's reliability standard. The wide variety in the capacity rating, configuration, custom specifications, and age of transformers leads to variability in the effects of GIC on specific transformers. A third tier of analysis is to consider the impact of harmonic currents generated by saturated transformers beyond removing vulnerable components. According to the NASA Living With a Star Institute Working Group, such analyses have been conducted by the research departments within utilities. Indeed, the first such harmonic simulation at the scale of a transmission owner's grid was published in 2015 by Dominion Energy of Virginia and its regional transmission organization, PJM Interconnection. Commercial software to calculate the effect of GIC-induced harmonics on the electric grid is not generally available. We spoke with grid software vendors that are integrating GIC and harmonic analysis capabilities for existing grid models.

Another reason that there is a lack of consensus among studies relates to uncertainty in the local geoelectric field. The

[37] *Geomagnetic Disturbance Reliability Standard*, 83 Fed. Reg. 23854 (*proposed* May 23, 2018).

relatively sparse coverage of magnetic observatories, particularly in the contiguous United States, limits the ability to monitor GMD in areas without magnetic observatories or variometers, which measure changes in the geomagnetic field. Even when the GMD is measured at nearby magnetic observatories, Earth resistivity required to calculate the geoelectric field in stage 6 is often the dominant source of uncertainty in GIC calculations. Earth resistivity is approximated either across vast regions using one-dimensional models or using local survey measurements. In the latter case, geologic surveys, such as the National Science Foundation funded EarthScope program, measure Earth resistivity as a function of frequency and spatial resolution relevant to GIC calculations.[38] According to USGS officials, changes in Earth resistivity can be localized. For example, Earth resistivity varies by about a factor of 10,000 within a Midwest region otherwise described by a single, one-dimensional ground resistivity model. The variation in Earth resistivity can vary greatly even across distances as short as one fifth mile. In addition to earth resistivity, geoelectric field enhancements can be caused by geomagnetic variations within the GMD itself. Geoelectric field enhancements that result from the geomagnetic conditions, in contrast to Earth-related enhancements, may occur at different times, locations, and of varying durations during a GMD. Accounting for localized enhancement requires careful consideration in modeling approach. However, lack of data may necessitate approximating the geoelectric field as uniform across the region of interest. According to NERC officials, the state of the art in commercially-available tools uses the uniform-field approximation. While a uniform geoelectric field is sufficiently accurate in many situations, it may fail to account for GMDs where localized areas are subject to high levels of geoelectric fields.

Calculating GIC and its effects requires data on grid components beyond those for a typical AC power flow analysis. GIC is similar to DC current, and existing AC grid models may not contain all of the pertinent characteristics.[39] Some transformer manufacturers and software vendors can provide models that calculate the response of transformers to GIC. Understanding the potential impact of GIC on a specific transmission system requires detailed analysis of transmission elements, such as transformers, but system operators may lack access to some of the needed data. Additionally, the substation grounding resistance is approximated in many studies yet can vary by a factor of 10 between substations. Power flow—used to calculate the effect of GIC on the stability of the transmission grid—is a function of the system topology, including the location and interconnectedness of transmission lines, transformers, and load. While calculating GIC flow from solar phenomena or the ensuing GMDs (stages 1 to 7) is necessary to predict or forecast GIC, these data are not currently used in the real-time operations of the power grid. Ultimately, the electric power industry

[38] Such survey data can be used to construct three-dimensional models of Earth resistivity, but the survey measurements can also directly be used for GIC modeling.

[39] Electric grid modeling tools were not designed with DC currents in mind. Most common grid simulation tools operate in the frequency domain and are not originally designed to calculate the propagation of harmonics. Software vendors note that the industry is working toward common standards for interoperability of models.

could measure GIC flowing through at-risk equipment and take action to mitigate its effects.

In some cases, ongoing research addresses some of these knowledge gaps so that the response of the electric grid to a large GMD can be assessed more accurately. For example, NASA scientists and other researchers are exploring the physical limit of GMD (stages 1 to 5). Vendors are developing and beginning to release GIC packages for commercially-available grid modeling tools (stage 7), although advanced capabilities to model transformer heating and harmonics are not yet available as features of commercial software packages common in the electric power industry. Studies generally make assumptions or engineering estimates about characteristics of the electric grid used in stages 7 and 8. Grid models used to calculate GIC in stage 7 may estimate pertinent details about substation grounding resistance, transmission line orientation, and the DC resistance of transformers. According to NERC, grid stability issues and voltage collapse are a likely impact of GIC; the more detailed simulations at stage 8 can model the underlying processes.

Another area of research is the extent to which GIC may be mitigated through modified operating procedures and improved control and protection systems. Research to refine geomagnetic and geoelectric field scenarios (stages 5 and 6, respectively) will help reduce uncertainty and improve industry preparedness. For example, an updated geoelectric field map, which is the product of USGS and NOAA cooperation, provides local data that industry can use for its vulnerability assessments and mitigation measures. Other ongoing interdisciplinary work brings together space scientists, geophysicists, and electric power industry researchers to advance knowledge and refine risk assessments. NERC and the Electric Power Research Institute (EPRI) collaboratively developed a GMD research plan in response to FERC direction. The research plan focuses on improving the benchmark GMD event and Earth resistivity models, evaluating available tools for calculating the geoelectric field, refining harmonic and thermal analysis, and improving collection of GMD and GIC data. According to NERC, the ongoing research will advance understanding of GMD events and the potential impact on the reliable operation of the electric transmission grid.

3 Technologies Are Available and Under Development That Could Limit the Effects of Geomagnetic Disturbances on the Electric Grid

3.1 Some types of electric power transmission equipment currently in use can help prevent or mitigate the effects of geomagnetic disturbances

3.1.1 The use of certain transformer designs can limit the effect of geomagnetically induced current on transformers

Saturated transformers are the root causes of nearly all GIC-induced disturbances in transmission systems, but there are differences in GIC susceptibility of transformers used in electric power transmission. Generator step-up transformers and transmission-to-distribution step-down transformers are usually wye-wound with grounded neutrals on high-voltage sides and delta-wound on low-voltage sides and GIC flowing through the grounded wye windings can cause saturation in transformers. Autotransformers are sometimes used in transmission to connect transmission systems with different voltages. Autotransformer high-voltage sides and low-voltage sides share windings and neutral connections to ground. Therefore, GICs flowing in autotransformers have alternate paths, GICs can flow through neutral connections to ground or GICs can flow into transmission lines on the other sides of autotransformers. Division of GIC flow into other transmission lines and into ground affects GIC levels in autotransformers which can affect GIC-induced saturation. Delta-wound transformers are immune to saturation by GIC, because delta windings are not grounded, therefore, GIC cannot flow through the windings and saturate these transformers. However, high voltage-side delta transformers are not generally used in transmission.

Three-phase transformers with a specific design (core-form, three-limbed) are significantly less susceptible to saturation by GIC than other designs, which means it takes significantly larger levels of GIC in these transformers to reach similar levels of saturation. However, as transformers increase in power and voltage they grow larger and shipping constraints become a practical challenge – passing through tunnels, under bridges, and fitting on railcars. Shipping constraints suggest consideration of more GIC-vulnerable transformers. For example, a three-phase, three -limb, core-form transformer is at least twice as heavy as each phase of a three -phase transformer consisting of bank of three individual single-phase transformers. Therefore, it should be significantly easier to ship three lighter individual single-phase transformers than one heavier three-phase transformer. Shipping height can be reduced by adding limbs (e. g. by increasing from three limbs to five limbs) and single-phase transformers can be laid on their sides for shipping (shipping length is seldom a constraint). For these reasons many higher voltage and higher power transformers may be significantly more susceptible to saturation by GIC than they could be if shipping of three-phase, core-form, three-limbed transformers were practical.

Transformer overheating and resulting thermal damage can be mitigated by certain transformer designs. When transformers saturate, magnetic fields “leak” out of their magnetic core, which can heat nearby transformer components made of magnetic materials and induce large circulating currents in transformer windings. Overheated transformer components can damage adjacent insulating materials and produce combustible gasses in transformer oil. Some overheating can be reduced by using transformers that have replaced certain structural steel parts with nonmagnetic materials, such as nonmagnetic steel. Many transformers are also designed to reduce circulating currents under normal operating conditions. These designs are also very effective in reducing susceptibility to GIC. For instance, according to an electric power industry official who was personally involved with the aforementioned Salem plant incident, the transformers that failed at Salem were an older design. According to the electric power industry official, newer design practices reduce circulating currents under normal operating conditions and offer about a factor of six improvement in resistance to GIC-induced thermal effects.

3.1.2 The use of certain auxiliary equipment and improved protective relays can reduce the risk of service outages from GIC

Series capacitors can be used to improve power transfer capability of long transmission lines through an increase of active or real power transmission while maintaining the voltage stability of the line. Series capacitors compensate for losses in reactive power, which is needed to maintain voltage, as well as the magnetic and electric fields of transmission lines. Because reactive power cannot be transmitted as far as active power, it must be compensated or replenished in long transmission lines. A side benefit of series capacitors is they block GIC. However, care must be exercised in placing series capacitors in the electric power transmission system because blocking GIC in one section of the grid can affect GIC flow in other sections of the electric power transmission system. Therefore, it is necessary to evaluate the effect of series capacitors in sections of the electric power transmission system on other sections of the electric power transmission system before they are installed.

A disadvantage of series capacitors is that they are expensive. Series capacitors are large and operate at transmission line voltages. Therefore, they require large, expensive, high-voltage-insulated support structures. However, it may be possible to employ significantly smaller, less expensive capacitors on transmission lines that will block GIC but will not compensate for losses in reactive power.

Grid vulnerability to GIC can also be reduced by replacing electro-mechanical protective relays with microprocessor-based protective relays, sometimes referred to as digital protective relays.[40] When transformers saturate, they generate harmonics, which can lead to incorrect or undesired operation of protective relays and unintentionally isolate key equipment at times when it provides critical voltage support to the system. As a

[40]Microprocessor-based protective relays are actually computers running complex algorithms to sample, filter and operate on signals provided by sensors. Microprocessor-based protective relays may provide many protection and control elements in a single unit.

result, safety or operating margins may be reduced bringing the system closer to voltage collapse and, potentially, interruption in the availability of electric power. The misoperation of electro-mechanical protective relays was a primary contributor to the 1989 Hydro-Québec GMD-induced blackout. Microprocessor-based protective relays, which consolidate several functions and provide protection via electronic circuitry, are less susceptible to misoperation when subjected to GIC-induced harmonics because they can be programmed to operate properly when subjected to these harmonics.

Inductors or resistors on neutral grounds are generally used for safety purposes, but they can also reduce GIC, though their effectiveness is uncertain. A study of the Finnish 400 kilovolt transmission system, which included systematic variation of the orientation of the geoelectric field, found an average of about a 50 percent reduction of GIC using neutral grounding inductors. A simplified calculation by NERC showed neutral grounding resistors could reduce GIC by about 80 percent. However, an EPRI study found that in order for neutral grounding resistors to approximate the GIC reduction performance of neutral blocking capacitors (which are discussed below) would require larger resistance values that would no longer solidly ground transformer neutrals and might adversely affect transformer insulation.

3.2 Technologies designed specifically to limit geomagnetic disturbance effects hold promise, but are not ready for widespread operational deployment

We found one GIC-mitigating system that has been developed, operationally tested, and piloted. However, following initial operational tests, the transmission system operator stated that the system was not yet ready for widespread deployment. There are other GIC mitigation technology concepts, but we did not find any that have been developed or tested.

The GIC-mitigating system that has been developed and operationally tested is based on GIC-blocking neutral capacitor technology. This technology places capacitors in neutral-to-ground connections on wye-wound, grounded neutral transformers. Similar to series capacitors, these capacitors provide high impedances to GIC—effectively blocking GIC—while providing low impedances at electric power transmission frequencies—not impeding desired neutral current flow at electric power transmission frequencies.

The primary advantages of GIC-blocking neutral capacitors over series capacitors are that only one neutral blocking capacitor is needed per transformer instead of three series capacitors, one for each of the three individual phases on transmission lines. Further, GIC-blocking neutral capacitor systems are less costly because they normally operate at very low voltages and currents compared to those on transmission lines. Therefore, GIC-blocking neutral capacitors do not require large, expensive high-voltage-insulated support structures. The primary disadvantage of GIC-blocking neutral capacitors over series capacitors is that neutral capacitors do not block GIC generation; GIC can still be generated in the transmission system and GIC blocked at one transformer neutral can flow through transmission systems to other transformers. GIC-blocking neutral capacitors are less effective in protecting autotransformers because GICs are only blocked from flowing to ground; GICs flowing in transmission lines on one side of autotransformers are not blocked from flowing through autotransformers into transmission lines on the other side.

Designs and laboratory tests of prototype GIC-blocking neutral capacitor systems date to the early 1980s. A prototype system was designed and tested on a distribution-voltage level system in the early 2000s. An engineering model of the GIC-blocking system was tested at DOE's Idaho National Laboratory in 2012. These tests demonstrated the engineering system model blocked simulated GIC, as expected. However, these tests were not full-up transmission system tests as the Idaho National Laboratory test grid has limited capabilities because the maximum voltage supported in transmission lines and transformers was 138 kilovolts, which is small compared to transmission system voltages of concern (200 kilovolts or larger). Further, during the tests, simulated GICs were 8-second-long pulses, and simulated GIC levels were limited to a maximum total of 30 amperes, which corresponds to 10 amperes per phase, which were much shorter than durations of GICs from representative GMDs. Concern for thermal damage to transformers from GIC starts at 225 amperes, which corresponds to 75 amperes per phase.

This same engineering model of the GIC-blocking system was updated and tested on an operational 345 kilovolt transmission system in 2015. During initial tests, the updated engineering system model blocked GIC fourteen times, as designed, during a 2-day-long strong geomagnetic storm (G3) in June 2015. However, in a submission to FERC, the transmission system operator stated that while this GIC blocking technology holds promise, a number of technology challenges must be successfully resolved before wide spread deployment of such GIC blocking devices is advisable. The transmission system operator's assessment was based on three factors:

- First, the operator stated that careful study is needed to design, install, operate, and maintain these devices because conventional planning models do not contemplate the presence of GIC-blocking devices. Therefore, it is challenging to understand the operating consequences of GIC-blocking devices on the safe and reliable operation of transmission systems.
- Second, the operator stated that rigorous testing and operating requirements are needed before the devices are accepted by the industry and widely deployed. Historically, taking a rigorous approach has resulted in a highly reliable and dependable transmission grid. It stated that introducing new, cutting-edge assets on a wide scale without this same rigor is risky and does not appear to be advisable based on the initial operating experience with this GIC-blocking device.
- Third, the operator stated that because this technology and its application were relatively new, other

> electric power suppliers do not have the benefit of electric power industry technology and manufacturing standards with respect to these GIC-blocking devices. It stated that without electric power industry standards, electric power suppliers might deploy blockers that could cause problems for the transformers they are seeking to protect.

After the initial tests, the updated engineering system model continued to be operated on the operational transmission system during geomagnetic storms in 2016 and 2017. According to the GIC-blocking system developer, experience acquisition is on-going. During all activities on the operational transmission system from June 2015 to August 2018, the updated engineering system model has operated a total of 33 times over 756 days of service, during geomagnetic storms ranging from G1 to G4.

Also, according to the GIC-blocking system developer, while the updated engineering system model has been installed on the operational transmission system, there were many geomagnetic storms that did not generate sufficient GIC to trigger the updated engineering system model and it operated, as designed. It did not block GIC during storms that produced low levels of GIC. However, there have been no reported updated engineering system model exposure to GMDs that might result in blackouts and damage to transformers. Also, there have been no reports of transmission line-to-ground faults during a GMD that might have triggered the updated engineering system model that would have tested the system fault protection function. Therefore, there are no operational data on the performance of the updated engineering system model during potentially damaging GMDs or the system fault protection function.

While there are other GIC mitigation technology concepts, we found none that have been developed or tested. For example, one patented concept would cancel GIC-induced magnetic fields in transformer cores by routing transformer neutral current back to magnetic cores, winding neutral current in the opposite direction of the main windings to cancel GIC-induced magnetic fields. Conceptually, this should render transformers immune to GIC. We found no evidence this concept has been incorporated in a transformer and tested in an electric power transmission system.

4 Further Technology Implementation Will Depend on Electric Power Supplier Actions and the Availability of Proven Technologies

4.1 NERC standards related to geomagnetic disturbances specify the use of operational procedures, but the use of technologies may also be needed

In May 2013, FERC directed NERC to develop and submit for approval reliability standards that address the effects of GMDs on the reliable operation of the U.S. electric power grid.[41] In response to FERC's direction, NERC initially developed the reliability standards in two stages. In June 2014, FERC approved NERC's first-stage reliability standard on geomagnetic disturbance operations.[42] NERC reliability standard EOP-010-1 requires the development, maintenance, and implementation of operational plans from certain electric power suppliers that describe activities to be taken to mitigate the effects of GMDs.[43] FERC required that reliability coordinators and certain transmission operators prepare such plans by April 1, 2015.[44]

In September 2016, FERC approved NERC's second-stage reliability standard on the planned performance of transmission systems during geomagnetic disturbances.[45] NERC reliability standard TPL-007-1 requires certain owners and operators to periodically conduct GMD vulnerability assessments and to implement corrective action when critical vulnerabilities are identified.[46] FERC has required that certain electric power suppliers prepare such assessments and corrective action plans by January 1, 2022.[47]

According to NERC, the use of operational procedures is the quickest way to make changes to address the potential effects of GMDs on the U.S. electric power grid. They are also more adaptable as the risk posed by GMDs becomes better understood. NERC has identified several operating procedures that could be used during a GMD to mitigate its effects, including:

[41]*Reliability Standards for Geomagnetic Disturbances*, Order No. 779, 78 Fed. Reg. 30747 (May 23, 2013).

[42]NERC Reliability Standard, Geomagnetic Disturbance Operations, EOP-010-1 (approved by FERC at Order No. 797, *Reliability Standard for Geomagnetic Disturbance Operations*, 79 Fed. Reg. 35911 (June 25, 2014)).

[43]EOP-010-1, Requirement R3, at 2.

[44]Specifically, transmission operators that operate power transformers with a high-side wye-grounded winding with voltage greater than 200 kilovolts. 79 Fed. Reg. 35914-15, 35917-18.

[45]NERC Reliability Standard, Transmission System Planned Performance for Geomagnetic Disturbance Events, TPL-007-1 (approved by FERC at Order No. 830, *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events,* 81 Fed. Reg. 67120 (Sept. 30, 2016)).

[46]TPL-007-1, Requirement R4, at 2, and Requirement R7, at 4.

[47]Electric power suppliers subject to the standard include transmission owners and generator owners with facilities that include one or more power transformers with a high-side wye-grounded winding with voltage greater than 200 kilovolts and planning coordinators and transmission planners with such facilities in their planning area. FERC also directed NERC to make certain revisions in the standard that may delay the implementation dates for the preparation of vulnerability assessments and corrective action plans. 81 Fed. Reg.67122-23, 67135-36.

- Increasing operating reserve margin so that equipment can better tolerate any GIC effects by reducing load, starting off-line generation, or returning outage equipment back to service and delaying planned service;
- Modifying protective relay settings to prevent unnecessary "nuisance" misoperation due to GIC; and
- Removing vulnerable systems and equipment from service to prevent their damage from GIC.

EOP-010-1 requires the implementation of operating procedures to mitigate the effects of GMD that would be initiated based on a predetermined condition,[48] such as NOAA information on forecasted or current severe GMD events. The initiation of operating procedures could also be based on observation of GMD effects on an electric power supplier's equipment. For example, the use of GIC measurement devices can improve situational awareness during a GMD event by allowing real-time measurement of the flow of GIC through the transmission network. Multiple GIC measurement devices are likely needed to provide electric power suppliers with sufficient information to take actions to mitigate the effect of GIC. For instance, placing devices near key transformers may provide information on the level of GIC being encountered at the transformer and the potential for saturation, which could allow for corrective actions, including taking the transformer out of service before permanent damage occurs. As part of its order approving TPL-007-1, FERC concluded that additional collection of GIC measurement data is necessary to improve the collective understanding of the threats posed by GMD events, as well as situational awareness during a GMD event. As a result, FERC directed NERC to specify requirements for selected electric power suppliers to collect such data as part of its revision to the standard.[49] Further, the National Space Weather Action Plan directed DOE to develop a plan for a national GIC and grid monitoring system.[50] When we met with DOE officials in April 2017, they stated that Idaho National Laboratory had produced a draft plan in consultation with the electric power industry, FERC, and Canada.

The ability to detect the effects of GIC on transformers is also useful to be able to mitigate the effects of GMD on the reliable operation of the transmission system. For instance, being able to detect harmonic currents generated by transformer saturation could be accomplished through the use of harmonics monitoring devices or determined through protective relay operations, such as the unintentional disconnection of capacitor banks. The use of real-time temperature and dissolved gas monitors in transformers could also provide insight into transformer effects due to GIC and allow for electric power suppliers to take responsive actions.

While TPL-007-1 also permits the use of operating procedures as a part of a corrective action plan, the standard suggests the plan could include the installation, modification, retirement or removal of generation or transmission technology and protection systems.[51] Though the implementation of

[48]EOP-010-1, Requirement R3, at 2.

[49]FERC Order No. 830, 81 Fed. Reg. 67131-32.

[50]National Science and Technology Council, *National Space Weather Action Plan* (Washington, D.C., Oct. 2015).

[51]TPL-007-1 Requirement R7, at 4.

technology will be slower and more costly than the use of operating procedures, in certain instances, it may be the most effective way to address any identified critical vulnerabilities to GMDs in the transmission system.

4.2 Further use of technology by electric power suppliers depends on a variety of factors

The need for further technology implementation to mitigate the effects of GMDs on the U.S. electric power grid will depend on a variety of factors. First, there needs to be a demonstrated need for technologies that is based on an understanding of the risks posed by GMD. In March 2016, we previously reported that federal agencies do not have a full understanding of the risks posed by electromagnetic events.[52] According to the National Infrastructure Protection Plan, to assess risk effectively, critical infrastructure partners—including owners and operators of the critical infrastructure and government agencies—need timely, reliable, and actionable information regarding the components of risk: threats, vulnerabilities, and consequences. According to the 2017 Quadrennial Energy Review, the lack of access to this kind of information represents a challenge to federal agencies to enhance the security and resilience of the grid. For instance, one key data gap is a lack of information on risk mitigation practices at the electric power supplier level, including information regarding participation in risk mitigation programs, specific risk mitigation practices, and details on critical parts of the electric grid, such as transformers. In 2016, DOE concluded that a significant modeling gap currently exists because traditional power system planning models do not including substation grounding or transformer configuration details, which are crucial to being able to model the flow of GIC in the power system. Consequently, the ability to predict GMD risks on the U.S. electric grid is inhibited. Federal agencies must rely on electric power industry data collection activities to understand the vulnerability and security landscape of the electric grid. As certain electric power suppliers implement the requirements of NERC reliability standard TPL-007-1 and periodically conduct geomagnetic disturbance vulnerability assessments, additional information that is needed to make technology implementation decisions could become available.

Second, electric power suppliers face several risks that can affect the reliable operation of the electric grid, which may also affect the management of GMD risks, including the use of technologies. Electric power suppliers face risks from terrestrial weather events, such as hurricanes, winter storms, and wildfire, and manmade events, such as physical or cyber-attacks on electric power equipment and facilities. According to DOE, the electricity sector has evolved to cope with several types of common events, and it understands how to recover from service outages caused by such events. However, for some high-impact events, electric power suppliers may have to determine how best to allocate their resources to prepare and mitigate the effects from those events because it is not practical to protect against service outages or equipment damage in all situations. Some high-impact events, such as a major hurricane or ice storm, pose greater risks because they generally occur more frequently than a severe

[52] GAO-16-243

GMD. Should electric power suppliers determine that actions are needed to address the threat of severe GMDs, decisions would still be needed to determine whether the use of operational procedures or the use of technologies would be more appropriate. Some electric power suppliers told us that it may be more practical to incorporate GMD protections into their systems as part of a normal lifecycle equipment replacement process, or as new equipment is purchased to expand service in new areas or to provide more reliable service in existing areas.

Third, because electric power suppliers are required to meet NERC operational reliability standards, they need assurance that any equipment that gets installed on the transmission grid will work as specified and will not negatively affect the reliable operation of the grid. Such assurance can be obtained through the use of electric power industry equipment standards and the testing of equipment against such standards. For existing transmission equipment, such as transformers and series capacitors, commonly accepted electric power industry equipment standards exist. Conformance of technology to common industry equipment standards helps provide assurance to electric power suppliers that the equipment works as specified and will not negatively affect the reliable operation of the grid. However, for technologies that are being developed to specifically prevent or mitigate the effects of GMDs, such as GIC-blocking technology, commonly accepted electric power industry standards have not yet been developed. Without such standards, it is difficult for electric power suppliers to gain assurance through the use of common testing methods against the standards that the equipment would operate as specified on the complex and interconnected electric grid.

Finally, there has been limited operational deployment or testing of these technologies. A testing facility to validate equipment functions or document systemic impacts of deployment at scale and under operating conditions would likely need a realistic high-voltage electric grid and the ability to simulate a large amount of GIC. For technologies that are designed to specifically prevent or mitigate the effects of GMDs, the inability to conduct operational tests of technologies with a large amount of GIC, consistent with a severe GMD, is a particular concern because electric power suppliers that may be interested in purchasing such equipment would have limited assurance that the equipment would operate properly when faced with a severe GMD. By Executive Order No. 13744, October 13, 2016, the President directed the Secretary of Energy, in consultation with the Secretary of Homeland Security, to develop a plan to test and evaluate available devices that mitigate the effects of GMD on the electrical power grid through the development of a pilot program that deploys such devices on an operational electrical power grid.[53] In January 2018, DOE officials stated that they had initiated work in September 2017 to develop a pilot program to test commercially available devices that can mitigate the adverse impacts of space weather on the electric grid. According to DOE, it completed the plan for the pilot program in April 2018 and has hired contractors to implement the plan and deploy mitigation technologies at one or more partner utilities.

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[53]Exec. Order No. 13744, § 5(a), *Coordinating Efforts to Prepare the Nation for Space Weather Events,* 81 Fed. Reg. 71573 (Oct. 18, 2016).

5 Strategic Implications

Threats to the reliability of the U.S. electric grid, including from GMDs, remain a national issue because long-term or large-scale disruptions to electricity could result in significant economic disruptions, impacts to public health and safety, and threaten national security. The federal government has taken actions to address the threat from GMDs in recent years including developing action plans for coordination of federal efforts and issuing standards for grid operators.

Federal policymakers face three broad questions that need to be addressed: (1) what is the likelihood of a large-scale GMD? (2) what is the risk such storms pose to the electricity grid? and (3) what are potentially effective solutions to mitigate the effects of a large scale GMD? Efforts are underway to address aspects of each question that will help inform whether additional efforts are needed to prevent or mitigate the effects of GMDs on the U.S. electric grid.

With regard to the first question, the likelihood of a GMD large enough to potentially cause damage to the U.S. electric grid is not fully understood. Despite efforts to better understand large GMDs, it is not currently possible to offer a definitive view on the likelihood of a large GMD, based on our review of the available evidence and input from experts. In part, this is because these events occur so rarely. Since 1932, we found only four GMDs have led to large-scale electric power outage or transformer damage. The largest recorded GMD, the Carrington event in 1859, predated the existence of the electric grid as well as detailed measurements of solar, space, and Earth conditions relevant to GMDs. Ongoing federally-funded research into solar physics, such as NASA's recently launched Parker Space Probe, may improve our understanding of the sun and how it causes space weather, and lead to improved assessments of the likelihood of large GMDs.

With regard to the second question, the extent to which a large GMD could cause a large-scale, long-duration electricity service outage in the United States is not fully understood, but work is underway that could increase understanding. The most persuasive studies we reviewed concluded that the most likely effects of a large GMD would be service interruptions that are neither long-term nor large-scale. However, in the event of a significantly larger GMD, on the order of magnitude of the 1859 Carrington event, there remains some uncertainty about the potential level of impact. Based on our work, the disruption or damage the most extreme GMDs can cause on the grid is the result of GIC flow in transformers. A NERC GMD reliability standard provides a benchmark to estimate the impact on the electric transmission system from a large GMD. Conducting such estimates is challenging because the wide variety in transformers, including model, age, and power capacity, could lead to significant variability in the effects on GIC on specific transformers. It is also challenging to incorporate the effects of harmonics on electric grid equipment, which are important because harmonics caused by GIC led to the only known electric service outages to result from GMDs in 1989 and 2003. NERC's GMD research work plan, in part, proposes to develop guidelines and tools to perform system-wide assessment of GIC-induced harmonics which, when completed and implemented, should improve the understanding of the effects that large GMDs and its resulting GIC flow could have on grid performance.

Finally, with regard to the third question, potential solutions to prevent or mitigate the effects of GMDs on the electric grid could include operational procedures or, eventually, the integration of new technologies. The recently implemented NERC GMD reliability standards direct certain grid operators to document and implement operational changes when a GMD occurs, but NERC recognizes that the use of technologies may also be beneficial. Unfortunately, there is little operational data on the effectiveness of currently available technology solutions to mitigate the effects of a large-scale GMD. Obtaining such operational data would require high-voltage transmission lines and transformers that could be exposed to simulated GIC at potentially damaging levels and configured to measure impacts on the equipment being tested, the other equipment on the system, and overall power flows. In response to a 2016 executive order, DOE is developing a pilot program to test and evaluate technology solutions on an operational electric power grid. This work, when completed, may help validate the operational viability of the most promising technologies for integration into the operational grid.

Policy decisions on further federal actions to prevent or mitigate the effects of GMDs on the U.S. electric grid will be better informed through an improved understanding of the likelihood and intensity of potentially damaging GMDs, the vulnerability of the grid, and the operational performance of potential solutions. Without better information to address these broad questions, it will be difficult for federal decision-makers to determine whether the risk posed by GMDs warrants specific federal actions to address it or to determine the appropriate solutions to prevent or mitigate the effects of such GMDs on the U.S. electric grid.

6 Agency Comments

We provided a draft of this product to the Departments of Commerce, Defense, Energy, Homeland Security, and the Interior; NASA; and FERC for their review. Each agency provided technical comments, which we incorporated as appropriate. We also received technical comments from NERC and EPRI, which we incorporated as appropriate.

We are sending copies of this report to the appropriate congressional committees and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Timothy Persons at (202) 512-6412 or personst@gao.gov or Frank Rusco at (202) 512-3841 or ruscof@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix II.

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Appendix I: Objectives, Scope, and Methodology

In this report we address the following questions:

1) What is known about the potential effects of geomagnetic disturbances on the U.S. electric grid?
2) What technologies are available or in development that could help prevent or mitigate the effects of geomagnetic disturbances on the U.S. electric grid, and how effective are they?
3) What factors could affect the development and implementation of these technologies?

We also discuss the strategic implications of the effects of geomagnetic disturbances on the U.S. electric grid.

To address all three research objectives, we met with federal agencies involved with geomagnetic disturbances (GMD) and their effect on the electric power grid, including the Department of Homeland Security, the Department of Energy and its national labs, the Department of Defense, the Federal Energy Regulatory Commission (FERC), the Department of the Interior's U.S. Geological Survey and Bureau of Reclamation, the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center within the Department of Commerce, and the National Aeronautics and Space Administration (NASA). We also met with electric power grid industry organizations, including the North American Electric Reliability Corporation (NERC), electric power suppliers, including the Department of Energy's power marketing administrations, and manufacturers of electric power grid components.

We limited the scope of our review of the U.S. electric grid to the contiguous United States because of the isolation of Alaska's and Hawaii's electric power system. Further, FERC's authority is limited to interstate transmission of electric power, which would not apply to these two states.

Further, we conducted a literature review using articles and reports identified in the following three ways:

1) searches of databases using Scopus and Proquest,
2) interviews with agency officials, electric power suppliers, and other electric grid industry stakeholders, and
3) references in literature.

We used Scopus to identify the most recent 100 articles or conference papers using the search terms "geomagnetic event" and "geomagnetic disturbance". We selected the most relevant studies for further review, and mined the abstracts for additional search terms to better refine results. We then used Scopus and Proquest to search for these additional terms, including "geomagnetic storms", "reactors", "transformers", and "controllers" to capture transmission grid components potentially impacted by geomagnetic disturbances, and "model validation", "harmonic analysis", and "predictive modeling" to capture methodologies used to determine GMD risks. The search was restricted to studies published since 2011. We also reviewed studies identified through our interviews with agency officials, electric power suppliers, and other key stakeholders. We reviewed the references in the in the aforementioned studies to further select the most highly cited peer-reviewed publications. We assessed the methodologies used in these studies and determined them to be sufficiently rigorous to provide information about the potential effects of GMD events on the electric grid.

We interviewed representatives from 13 U.S. and Canadian electric power suppliers—entities that own or operate generation or transmission infrastructure that conduct planning and generation, transmission, and distribution operations.[1] We selected these 13 electric power suppliers based on input from the Department of Energy, NERC, electric power industry associations, and research institutions as to which suppliers had taken steps to prepare for and mitigate impacts from electromagnetic events. We also considered, among other things, the following characteristics: (1) efforts or plans to install GMD mitigation equipment or technology; (2) efforts or plans to develop specific mitigation processes, procedures, or other operational actions; (3) infrastructure, such as length and voltage of transmission lines; (4) high-voltage equipment, including transformers over 230 kilovolts; (5) geomagnetic latitude; and (6) experience with GMD-related service disruptions.[2] We included three Canadian electric power suppliers among the 13 suppliers we interviewed due to their (1) experiences with GMD events, (2) research on the impacts of GMD, and (3) actions taken to prepare for and mitigate GMD events.

We conducted site visits to 6 of the 13 suppliers to supplement our understanding of the operation of the electric power grid, the potential effects that GMDs could have on the grid, and the prevention and mitigation strategies that are available to the suppliers when faced with a GMD.[3] We selected sites that are knowledgeable about the effects of GMDs on its grid, which were identified through our interviews and our review of literature, including those sites that have prior experience with geomagnetic disturbances, have conducted risk assessments or modeling of the potential effects, or have implemented technologies that could prevent or mitigate the effects of geomagnetic disturbances. During these visits, we met with organization officials; observed operations and facilities, and viewed equipment potentially vulnerable to GMD, such as high-voltage transformers. While we cannot generalize the information we learned from these selected suppliers to all U.S. and Canadian suppliers, they provided insight on what electric power suppliers may know regarding the potential effects of electromagnetic events on the electric grid, as well as steps suppliers may be taking to prepare for and mitigate such effects.

We interviewed five industry associations—Edison Electric Institute, the Electric Power

[1]For the purposes of this report, we define "electric power suppliers" as entities that own or operate generation or transmission infrastructure, as well as those with responsibility for planning and overseeing the grid and for selling electric power to consumers.

[2]The volt is the unit of measurement for the electromotive force that causes electricity to flow through a conductor, with a kilovolt representing 1,000 volts. The classification of "high voltage" transmission varies, but generally ranges from 230 kilovolts up to 765 kilovolts in North America.

[3]The six U.S. and Canadian electric power suppliers we visited were Bonneville Power Administration, Dominion Energy, PJM Interconnection, Hydro-Quebec, Peak Reliability, and Western Area Power Administration. The seven electric power suppliers we interviewed by phone or received written responses from were American Transmission Co., Central Maine Power, Electric Reliability Council of Texas, Exelon Corp., the Southern Company, Hydro One (Ontario), and Manitoba Hydro.

Supply Association, the National Association of Regulatory Utility Commissioners, the National Electrical Manufacturers Association, the National Rural Electric Cooperative Association—because of their specialized knowledge and experience with the electric power industry. We also met with the Electric Power Research Institute to discuss its research into GMD effects on the electric grid and possible mitigation strategies. Based on input from the Department of Energy, NERC, electric power suppliers, and industry officials, we interviewed representatives from ABB and Mitsubishi Electric Power Products, two manufacturers of large power transformers with facilities in the United States. We met with representatives of PowerWorld and POWERSYS Solutions, companies that develop electric grid modeling software, to discuss simulations of GMD impact on high-voltage networks. We also met with officials from Emprimus, the designer of a prototype device for mitigating the effects of GMD on the electric grid.

To determine what is known about the potential effects of GMD on the U.S. electric grid, we identified and analyzed data on GMD occurrences and analyzed and summarized corresponding reports identified through our literature review relating to any damage or disruptions related to the occurrences. We identified and analyzed data on the frequency and intensity of GMD events from 1933 through 2017, since the start of the first solar cycle within the GMD record maintained by the GFZ German Research Centre for Geosciences. According to NOAA officials, the GFZ German Research Centre for Geosciences maintains the authoritative historical record of these data. We assessed the reliability of these data by testing for missing data, outliers, or obvious errors. We found the data to be sufficiently reliable to report on the number and intensity of GMD events occurring from 1933 through 2017. We grouped the intensity of GMD events using NOAA's Space Weather Scale for geomagnetic storms and by solar cycle. We used information about the beginning of each solar cycle from NASA.

Further, we used the results of our literature review to summarize the known potential effects of GMD on the U.S. electric grid. We identified areas where the studies had common findings, as well as those areas where the studies had divergent findings. We supplemented our understanding with information obtained through our interviews with federal, electric power supplier, and industry officials. In addition, we also met with the organizations that issued or commissioned the studies that we reviewed, including FERC, NERC, the Electric Power Research Institute, Idaho National Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory, and Natural Resources Canada.[4]

To identify technologies that are available or in development that could help prevent or mitigate the effects of geomagnetic disturbances on the U.S. electric grid, we used the results of our literature review and our interviews with electric power suppliers that have deployed such technologies. We used documentation provided by large power

[4]The national labs are among 17 national labs overseen by the Department of Energy to perform scientific research on a range of large-scale, complex issues for the federal government and other entities. We conducted a site visit to Idaho National Laboratory in conjunction with our site visit to nearby electric power suppliers. Natural Resources Canada is a federal department in Canada responsible for natural resources, energy, minerals and metals, forests, earth sciences, and mapping.

transformer manufacturers and our interviews with them to understand how transformer design can affect their susceptibility to GMD effects. For technologies that have not been widely deployed, we reviewed available test documents and interviewed officials from the technology developer and the testing organization, as appropriate. We also used information from and our interviews with researchers, including the Electric Power Research Institute and the national labs, to better understand technologies that are available or in development that can help prevent or mitigate GMD effects.

To identify factors that could affect the development and implementation of these technologies, we reviewed FERC orders and NERC reliability standards that require certain suppliers to take steps to assess and prepare for GMD impacts.[5] We interviewed FERC and NERC officials to discuss these standards and reviewed public comments submitted by stakeholders during the FERC rulemaking process. We also used our interviews with electric power supplier officials to understand the extent to which they had evaluated the impact of electromagnetic events on their specific generation systems or transmission networks and what they had learned from these evaluations. We also used the interviews to identify steps they had taken to comply with NERC reliability standards as well as any additional actions to prepare for and mitigate potential GMD effects, such as replacement of older equipment or investment in spare transformer programs, including any reasons why they have or have not taken actions to mitigate potential GMD effects. We reviewed the National Space Weather Strategy, the National Space Weather Action Plan, an Executive Order on space weather, and relevant laws, including the USA PATRIOT ACT of 2001, the Critical Infrastructures Protection Act of 2001, and the Federal Power Act, and Department of Energy, Federal Energy Regulatory Commission regulations, and related guidance to understand their requirements and we requested updates on the progress on select requirements from the relevant federal agencies.[6]

Our research led us to three key questions that determine the strategic implications that federal decision-makers face as they determine whether further federal actions are needed to prevent or mitigate the effects of GMDs to the U.S. electric grid.

We conducted our work from February 2016 to December 2018 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[5] *Reliability Standard for Geomagnetic Disturbance Operations,* Order No. 797, 79 Fed. Reg. 35911 (June 25, 2014). *Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events,* Order No. 830, 81 Fed. Reg. 67120 (Sept. 30, 2016).

[6] Executive Office of the President, National Science and Technology Council, *National Space Weather Strategy* and *National Space Weather Action Plan* (Washington, D.C.: Oct. 2015). Exec. Order No. 13744, *Coordinating Efforts to Prepare the Nation for Space Weather Events*, 81 Fed. Reg. 71573 (Oct. 18, 2016).

Appendix II: GAO Contacts and Staff Acknowledgments

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In addition to the contacts named above, Kendall Childers, Jonathan Felbinger, Barbara Guffy, Michael Harmond, Richard Hung, Miles Ingram and Jon Ludwigson made key contributions to this report. Ben Atwater, Amy Bowser, Jehan Chase, Philip Farah, Dani Green, Michael Kaeser, Katrina Pekar-Carpenter, and Danny Royer also contributed to this report.

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