SOLAR STORMS EFFECTS ON NUCLEAR AND ELECTRICAL INSTALLATIONS

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"There are only two kinds of people who are really fascinating: people who know absolutely everything, and people who absolutely know nothing."
Oscar Wilde, Irish author.

INTRODUCTION

The Earth is subject to an 11-year cycle of periods of increased solar activity, as astronomers have known for centuries. They are associated with visible sun spots on the surface of the sun.

The events begin with thermonuclear explosion on the sun that swell up and bursts open on the sun's surface, releasing radiation and charged particles trapped in the solar wind.

The continuous but variable flow of particles and magnetic fields from the sun creates gusts that can quickly reach the Earth. Within hours, a Coronal Mass Ejection, CME, accompanied by an Aurora Borealis or "northern lights" or an Aurora Australis or "southern lights" bombards the Earth with geomagnetic disturbances.

Solar storms can disrupt communication and navigational equipment, damage satellites, and even cause blackouts by damaging power plants and electrical grid components

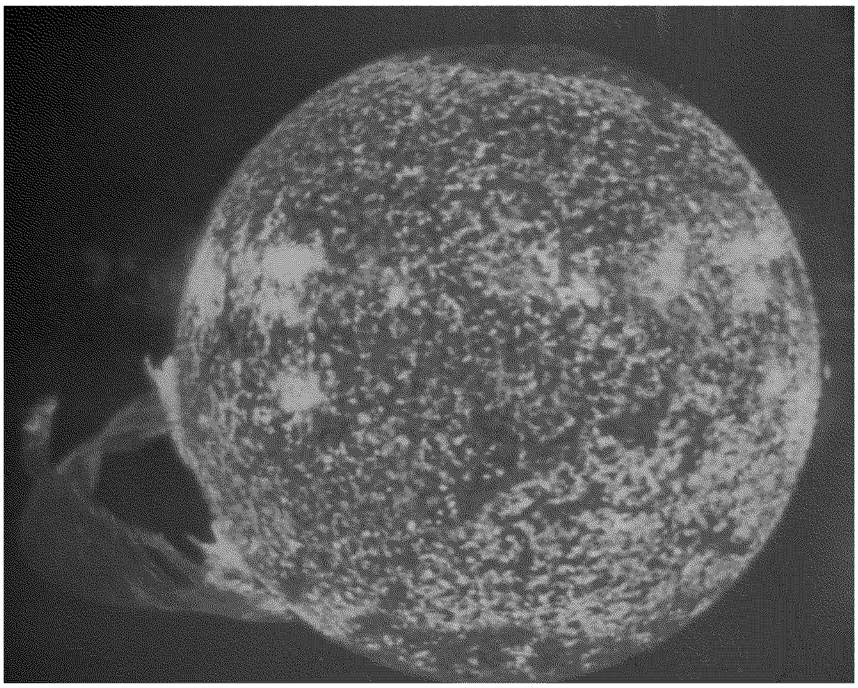

Figure 1. Solar flare showing the thermonuclear reactions sun spots and the magnetic fields eminences. Source: NASA.

Solar storms have effects on:

1. Radio communications fadeouts,
2. Auroras Borealis and Australis,
3. Disruptions in power lines,
4. Disruption in radio transmission,
5. Geomagnetic storms,
6. Ionospheric storms,
7. Radiation hazards to astronauts.

SOLAR WIND AND SOLAR STORMS

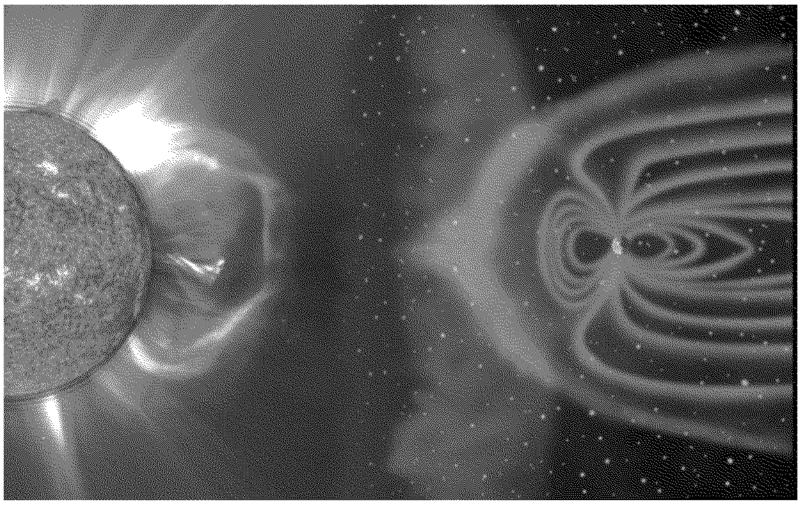

Figure 2. Solar wind and storms interaction with the Earth's magnetic field. Note that the sun is one million times the size of the Earth. Source: NOAA.

A solar storm has a bow shock that is stopped by the Earth's protective magnetosphere. The magnetic cloud of plasma can extend to 30 million miles wide by the time it reaches the Earth.

The magnetic field orientation of a Coronal Mass Ejection, CME is a major factor as to whether the Earth will suffer many consequences from any given CME. After a CME blasts from the sun towards Earth, a cloud of charged particles impacts our magnetosphere in 2 to 4 days.

The Earth is effectively electrically connected to the sun by a large-scale circuit. The consequences are dramatic: disruptions to communications satellites, interference with Global Positioning Systems, GPS and air traffic control.

The phenomenon can take down the high-voltage electric transmission system over wide swaths of the planet, blacking out more than 130 million people in the USA alone.

Secondary effects due to the loss of the electrical grid involve nuclear power plants shutdowns, water system failures, severe disruptions to natural gas pipelines, factories shut down for weeks or months, food rotting in unrefrigerated warehouses, and costs to the world economy.

The cost of the damage caused by a CME to the USA could total $1-2 trillion. More than 300 grounded electrical high-voltage transformers in the USA suffer damages so serious that they need to be replaced, putting intolerable strain on an already stressed supply chain.

Recovery takes as much as a decade, as the results wreck havoc with the USA and world infrastructure and economy.

This is fact, not science fiction according to the office of emergency response at the Federal Energy Regulatory Commission, FERC. It occurred before but with far less severe economic consequences. It is likely to happen again following a higher activity in the solar cycle.

EFFECT ON NUCLEAR POWER PLANTS

In 1989 a solar storm affected the Salem Pressurized Water Reactor, PWR in New Jersey. The 1,160 MWe Salem-1 nuclear power plant is located on an artificial island at the mouth of the Delaware River, along with two other nuclear units.

The solar storm induced a large current into the PJM 500-kV transmission system, which damaged the Salem Unit 1 step-up transformer, resulting in a large melted mass of copper and copper shot.

The transformer's winding insulation confined the damage, and the plant did not trip off during the solar flare. The plant operators discovered the damage after the storm. The transformer had to be replaced, at a cost of millions of dollars.

GEOMAGNETICALLY INDUCED CURRENT, GIC

As the charged solar particles in the solar wind arrive at the Earth, they cause rapid fluctuations of the Earth's geomagnetic field.

Induced Earth-surface potential and Geomagnetically Induced Currents, GIC, occur. GIC appears as a quasi-DC current or an AC waveform with a period of several minutes and appears as a DC current to the bulk electric grid system.

The consequences of this DC current are to drive transformer cores into saturation. This causes significant heating from stray flux, increases the Volts Ampère Reactive, VAR power losses that depress system voltages, and can damage the transformer itself.

MULTIPLE CONTINCENCY INCIDENT, MCI

The induced currents can precipitate a Multiple Contingency incident, MCI which, under certain operating conditions, can jeopardize the integrity of the bulk electric systems in North America.

The harmonic currents can cause the over-current relays to trip the capacitor banks because capacitors offer a lower impedance path for the harmonics.

The static VAR power compensators can trip for over-current or over-voltage protection.

The complex events resulting from the induced currents can take the electrical generators down along with the whole electric grid, as the electrical generators are not immune to the harmonic currents.

Those units that do not trip are still susceptible to damage from turbine blade vibrations and possible blades ejection.

EFFECT ON THE NORTH AMERICAN POWER GRID, 1989

When a solar storm strikes the Earth's magnetosphere, it creates a gust in the solar wind. On Friday March 10, 1989 such a storm affected northern Canada in a matter of days. The arrival of the solar particles caused severe disturbances in the planet's magnetic field.

According to a description by NASA:

> "On Friday March 10, 1989, astronomers witnessed a powerful explosion on the sun. Within minutes, tangled magnetic forces on the sun had released a billion-ton cloud of gas. It was like the energy of thousands of nuclear bombs exploding at the same time. The storm cloud rushed out from the sun, straight towards Earth, at a million miles an hour. The solar flare that accompanied the outburst immediately caused short-wave radio interference, including the jamming of radio signals from Radio Free Europe into Russia. It was thought that the signals had been jammed by the Kremlin, but it was only the sun acting up!"

On March 13, 1989 seven static VAR compensators on Hydro-Québec's, HQ giant La Grande high-voltage transmission network shut down in a matter of seconds. Induced direct current from the solar storm caused the transmission system voltage to drop, frequency to rise, and the line to trip off.

The rest of the HQ transmission system collapsed in seconds. It took nine hours to restore 18,000 MWe of power to the network. The solar storm left considerable wreckage in its path, including two La Grande 4 generating station step-up transformers, thyristor and capacitor banks at several units, and static VAR compensators across the system that were damaged or destroyed.

The effects on the North American electrical grid that connects Canada and the USA, except for the state of Texas that is connected to the Mexico's electrical power grid, were significant.

The Québec blackout was not localized. Some of the USA electrical utilities were affected. New York Power Authority lost 150 MWe of capacity the moment the Québec power grid collapsed. The New England Power Pool lost 1,410 MWe at about the same time. Service to 96 electrical utilities in New England was interrupted while other reserves of electrical power were brought online.

The USA had some excess spare capacity at the time. Across the USA, 200 power grid problems erupted within minutes of the start of the March 13, 1989 solar storm, without causing a complete blackout.

EFFECT ON COMMUNICATION SATELLITES

Some satellites tumbled out of control in space for several hours. NASA's TDRS-1 communication satellite recorded over 250 anomalies as high-energy particles impacted the satellite's sensitive electronics.

In the Space Shuttle Discovery, a sensor on one of the tanks supplying hydrogen to a fuel cell was showing unusually high pressure readings on March 13, 1989. The problem went away just as mysteriously after the solar storm subsided.

GLOBAL EFFECTS, 1989

Large geomagnetic storms can have a global reach and produce impacts to other developed power grids around the world.

In the UK, the March 10, 1989 storm is suspected to have caused damage to two 400 kV transformers. The operators of the power grid in the UK also understand that. Since 1989, the operators of the UK power system equipped their grid with transmission system static VAR and switched-capacitance devices for system voltage regulation. This makes their system less vulnerable to future geomagnetic storms.

Recent and lower intensity storms reached the Southern Hemisphere producing lower intensity, but long duration GIC disturbances in South Africa that caused permanent damages and loss of 15 EHV transformers in the South African Eskom system.

EARLIER SOLAR STORMS EVENTS, 1859, 1921, 2003

Larger storms than the 1989 one have occurred. In 1859, the largest known storm, called the "Carrington Event," after the British astronomer Richard Carrington struck Earth.

Another solar storm struck the Earth in May 1921, causing substantial destruction. Government experts have defined the 1921 storm as a 1 in a 100 years event. This does not mean it cannot happen more frequently than that, but gives an indication of its severity.

A minor solar storm in October-November 2003 took down the USA Federal Aviation Administration's new Global Positioning System, GPS-based navigation system for 30 hours and damaged electrical systems from Scandinavia to South Africa.

SOLAR STORM, 2011

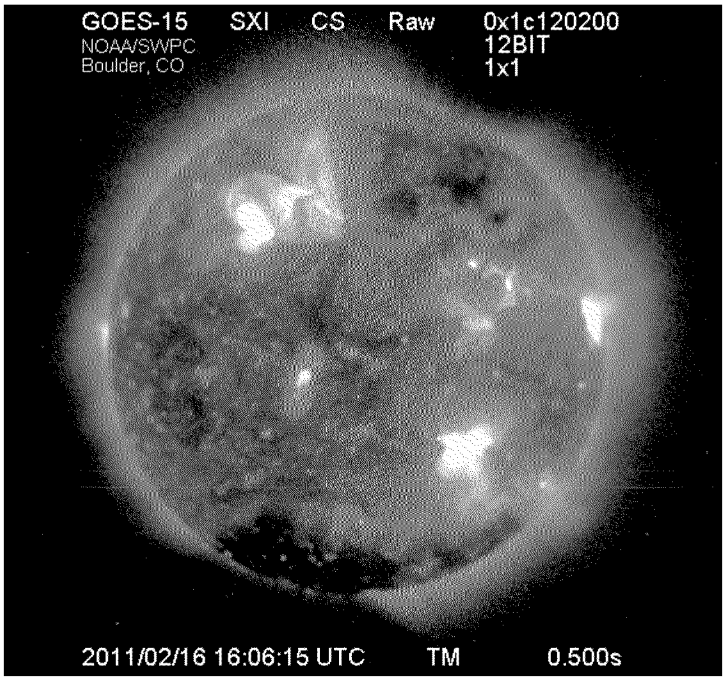

Figure 3. Solar storm on February 16, 2011. Source: NOAA.

Bright and dark regions of the sun in appeared in a solar x-ray image at the NOAA's Space Weather Prediction Center showed enhanced solar wind on February 16, 2011 with magnetic storminess. Effects included temporary radio blackouts, re-routed airplanes, increased risk of damage to electrical grids and satellites and brilliant auroras.

EFFECT ON MODERN ELECTRICAL SYSTEMS, INTERCONNECTEDNESS, CASCADE FAILURE

Modern storms can cause much more damage and disruption than earlier events, since the electrical and electronic infrastructures around the world are more ubiquitous, complex, and connected.

Power grids may be more vulnerable than ever because of interconnectedness. In recent years, utilities have joined grids together to allow for long-distance transmission of low-cost power to areas of sudden demand. Interconnectedness makes the system susceptible to wide ranging "cascading failures."

Larger, longer, and bigger transmission systems add to the vulnerability to GICs, by reducing the resistance of the grid. The miles of high-voltage transmission voltage in the USA have increased by a factor of 10 over the last 50 years leading to an effectively larger antenna.

SOCIETAL AND ECONOMIC IMPACTS, PREPAREDNESS

Considering the potential effects of an event similar of the May 1921 storm on the modern USA grid system, the risks involved loss of more than 350 high-voltage transformers and power outages to more than 130,000 million Americans.

The loss of electricity would spread across the physical infrastructure and would include water distribution affected within several hours; perishable foods and medications lost in 12-24 hours; loss of heating/air conditioning, sewage disposal, phone service, and fuel re-supply.

The threat of geomagnetic storms is well understood in the electrical utility industry, and much effort is being devoted to understanding and preparing for this contingency.

The Electric Power Research Institute, EPRI has been devoting considerable effort to studying geomagnetic storms since the 1989 event. It has produced voluminous work on the impacts of solar storms on electric systems, working through its SUNBURST project, which aims to "monitor, study, and mitigate" geomagnetically induced currents on the power grid.

With the solar cycle just passing the minimum and solar storm activity at a 50-year record low in 2010, it is easy to temporarily forget about solar storms and GICs. However, as a new cycle starts, predictions indicate that the next solar peak could be 30-50 percent higher than the peak of the last cycle."

HIGH IMPACT LOW FREQUENCY, HILF EVENTS

Solar storms, though potentially catastrophic, are not very predictable, in either frequency or strength. They represent what the utility industry calls "high-impact, low-frequency," HILF risks.

Solar storms are grouped with electromagnetic pulse events, which might be caused by the detonation of nuclear devices in the upper atmosphere by an adversary hoping to take down the high-voltage grid by causing an Electro Magnetic Pulse, EMP event.

Other HILF risks in the utility planning process include conventional weather effects, including tornadoes and hurricanes.

Utilities have spent large amounts on preparations for HILF risks, but passing costs on to customers, either in advance, or after a catastrophe, will be difficult in a political environment characterized by an anti-rate-increase attitude.

The insurance company Zürich Services Corporation published an analysis of the exposure of various industries to solar storms, including the prospect of replacing large high-voltage, grounded transformers at $10 million a pop. The study concluded that a large solar storm would be an event "beyond insurance."

RECOVERY TRANSFORMERS, RecX PROJECT

EPRI and the Department of Homeland Security, DHS worked on a project to design prototype recovery transformers that could temporarily replace damaged equipment after a storm.

The Recovery Transformer, RecX Project would build and pre-position truck-mounted single-phase 345 kV transformers as temporary fixes if a conventional three-phase, 345- kV machine were damaged.

The idea is to design a transformer that is smaller and easier to transport and quick to install. The goal of the project is to produce solid-state transformers that are smaller and lighter and could be transported by helicopter.

Storms 10 times worse than the 1989 event can occur and have occurred and offer a significant challenge since it would be the largest natural disaster the USA could face and needs to survive.

REFERENCE

1. Kennedy Maize, "The Great Solar Storm of 2012?" Power, January, 2, 2011.

APPENDIX

VOLT AMPERE REACTIVE, APPARENT POWER Q

In Alternating Current, AC power transmission and distribution, the Volt Ampère Reactive power or VAR is a unit used to measure the apparent reactive power Q in an AC electric power system where:

$$\begin{aligned} &\text{Reactive Power } Q = V_{rms}.A_{rms} \sin\phi \\ &\text{where: } V_{rms} = \text{rms voltage} \\ &\quad A_{rms} = \text{rms current} \\ &\quad \phi = \text{phase angle between voltage and current} \end{aligned} \quad (1)$$

Since AC power has a varying voltage, efficient power systems must vary the current in synchrony with the voltage.

VARs measure the unsynchronized "leading or "lagging" currents. VARs are the product of the root mean square, rms voltage and current, or the apparent power, multiplied by the sine of the phase angle between the voltage and the current.

When the phase angle between the load voltage and load current is out of phase by 90 degrees, this defines the VAR-reactive as:

$$VAR = V_{rms}.A_{rms} \sin 90^o = V_{rms}.A_{rms} [\text{Volt.Ampere}] \quad (2)$$

Note that the apparent power Q is different from the real power P.