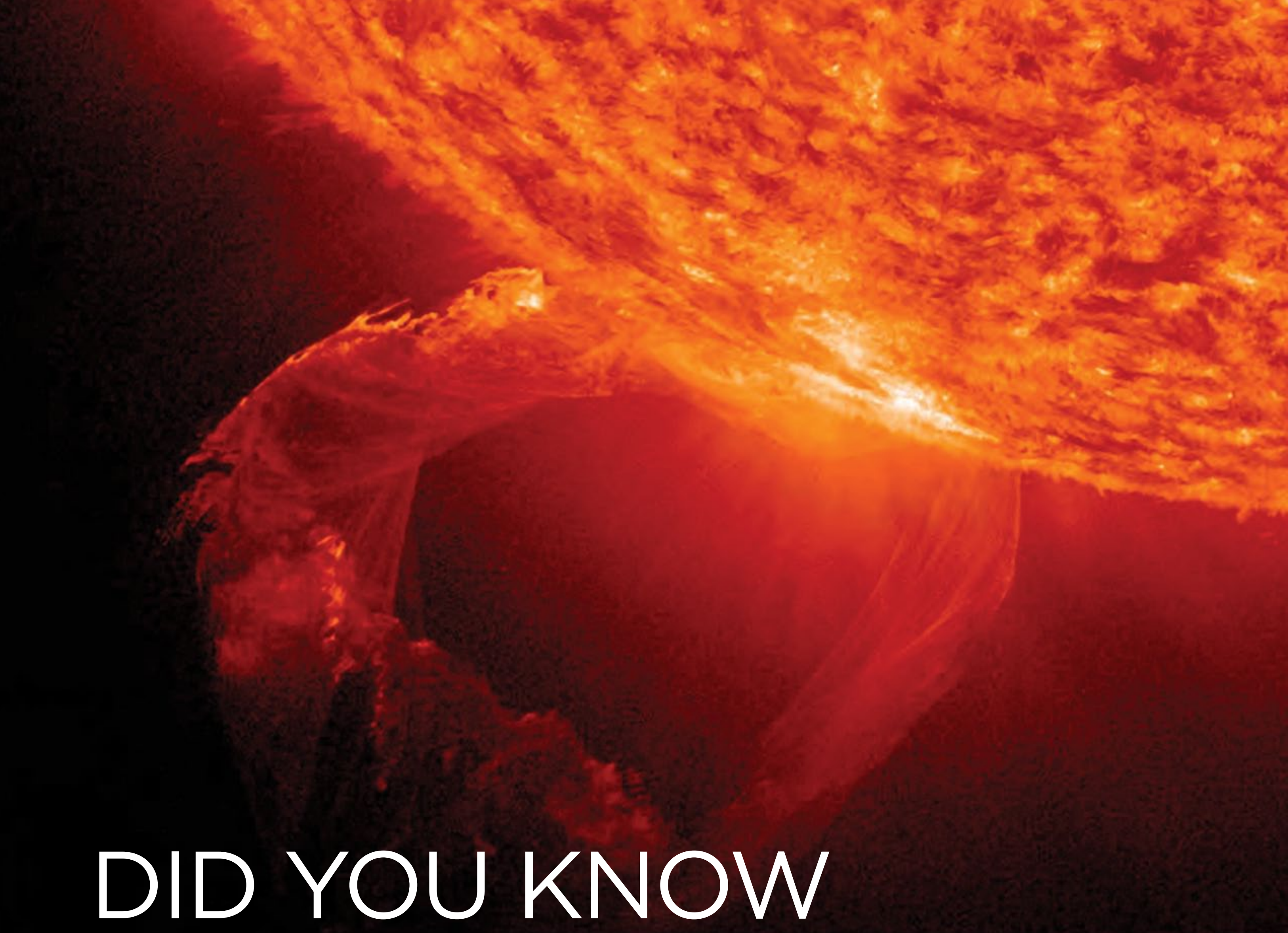


DID YOU KNOW SOLAR STORMS CAN ACTUALLY DAMAGE A TRANSFORMER?

By: Estefania Ruiz

Every year, there are certain solar events that take place. While we all back here on Earth have probably never seen or heard about this phenomenon, these events are the result of the Sun changing its magnetic polarity every 11 years, which is known as a "Solar Cycle" [1].

As the Sun's magnetic polarity gradually changes, solar activity increases displaying sunspots in the surface of the Sun. Thus, the number of sunspots is a good indicator of a solar cycle stage.

Sunspots can be perceived as temporary small magnetic poles that usually appear in pairs... one of them having a positive polarity, and the other a negative one.

The highest solar activity appears halfway through the Solar Cycle, and this is when more sunspots can actually be seen. This stage of the cycle is called "Solar Max." Figure 1 shows the Solar Max of year 2001.

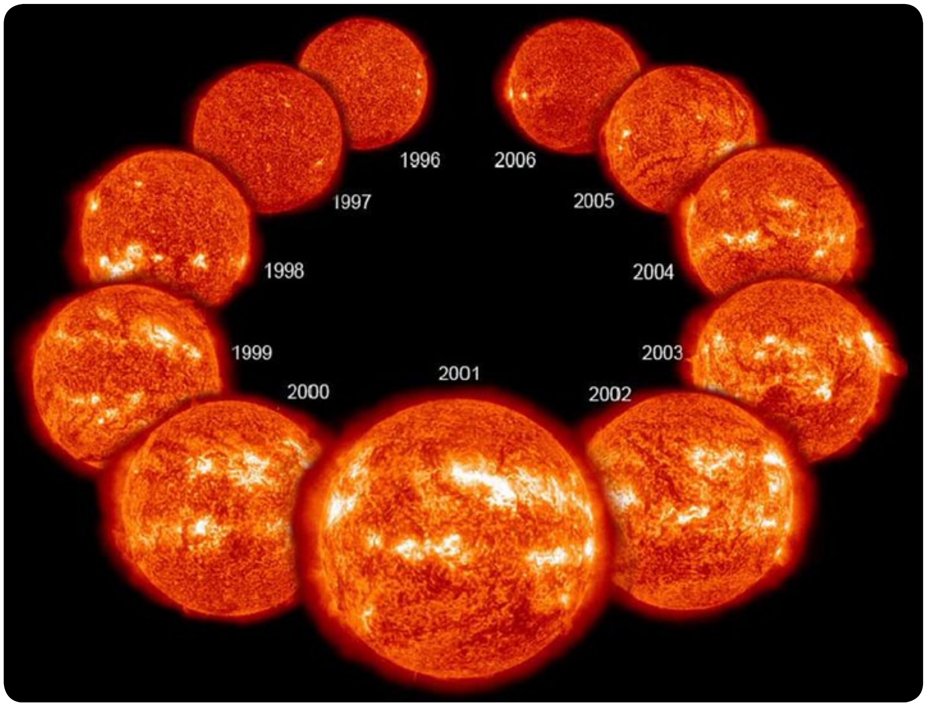


Figure 1. Images of the Sun during a Solar Cycle. Solar Maximum occurred in 2001 while in 1996 and 2006 there was a Solar Minimum. Image credit: NASA

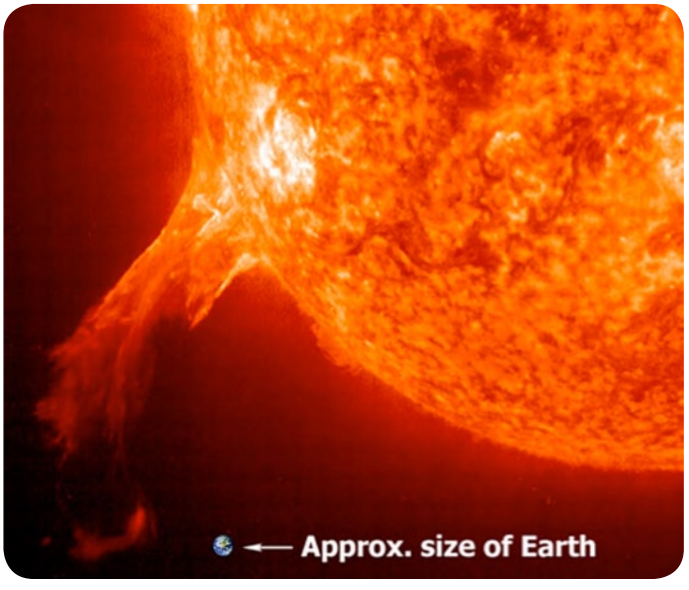


Figure 2 A. Close-up of an erupting prominence with Earth inset at the approximate scale of the image. Taken on July 1, 2002. Credit: SOHO, ESA & NASA.

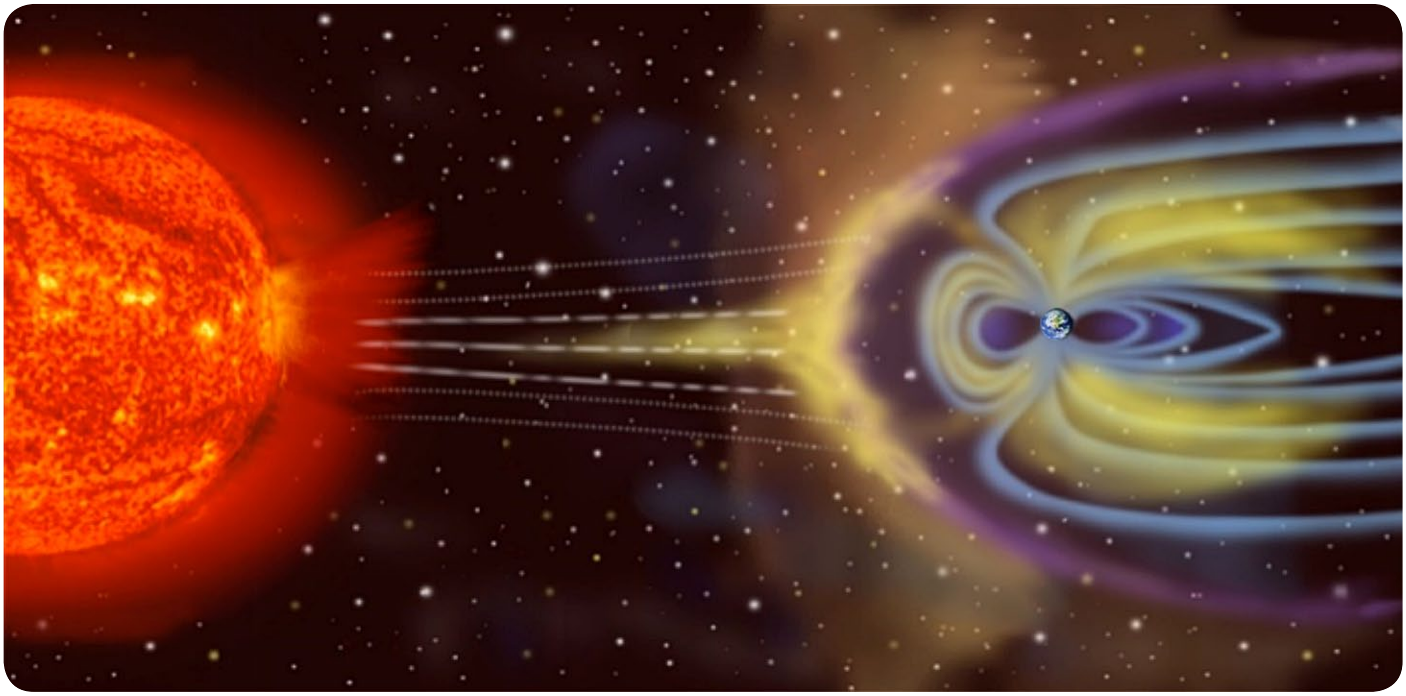
HOW DOES THIS SOLAR PHENOMENON AFFECT EARTH?

Solar flares are a huge burst of energy that usually comes hand in hand with the release of huge streams of charged plasma that travels at millions of miles per hour. These are called **CMEs** (Coronal Mass Ejections).

Depending on the magnitude and direction of the CMEs, these might cause a **Geomagnetic Disturbance** hitting Earth with tons of electrical charges and magnetic fields at a speed of approximately three million miles per hour. **Geomagnetic Disturbances** can affect the power grid, interfere with GPS, or even satellite- based communications systems.

[1] **Solar Cycle:** Every 11 years, the Sun's magnetic field goes through a cycle, known as the Solar Cycle.

Space science and Geoscience play relevant roles in assessing the effects of Solar Storms on Earth systems, helping engineers create simplified models to assess the effect on power transformers in aim to keep the electric grid stable.



¿WHAT IS GMD (GEOMAGNETIC DISTURBANCES)?

A GMD happens when the charged particles expelled by the Sun affect the geomagnetic field. The most critical GMDs are associated with Coronal Mass Ejections (CMEs).

Variations in the geomagnetic field cause large scale electric currents to appear in the ionosphere[2], near the Earth magnetic poles. These currents are also known as "Electrojets."

You have probably heard about the amazing lightning effect called "Aurora Borealis" or Northern Lights. These lights, typically only visible near poles, are the result of electrojets flowing into the ionosphere, which causes a temperature increase in the thermosphere[3] and the release of particles already trapped around Earth. With this, a chain reaction is produced and oxygen and nitrogen molecules release photons of light.

...But, then... how does this affect the electrical grid?

Geomagnetic field variations, caused by solar activity, create electrojets, which in turn induce electric fields onto the surface of the Earth, generating what is called GICs or Geomagnetically Induced Currents. These GICs can ultimately cause blackouts.

Geomagnetically Induced Currents (GICs) are quasi-DC currents because their frequency depends on the geomagnetic field variations which usually range between 0.0001 Hz to 1 Hz. GICs flow through the electric grid, which represent a closed loop where they can circulate. What happens is that they enter through **Grounded Transformer Neutrals**, flow through their windings, and circulate through the transmission lines until they reach another point with another grounded transformer.

[2] **Ionosphere:** A layer of charged particles, called the ionosphere, surrounds Earth. These extend from about 50 to 360 miles above the surface of the planet – shown in purple and not-to-scale in this image. Because the ionosphere swells in response to incoming radiation from the sun, the exact size and shape of the ionosphere can change throughout the day, and the daytime ionosphere is always larger than the nighttime ionosphere.
[3] **Thermosphere:** The thermosphere starts just above the mesosphere and extends up to 600 kilometers (372 miles) high. Aurora and satellites occur in this layer.

The magnitude of GICs will depend on ground conductivity, orientation, and intensity of the geomagnetic field.

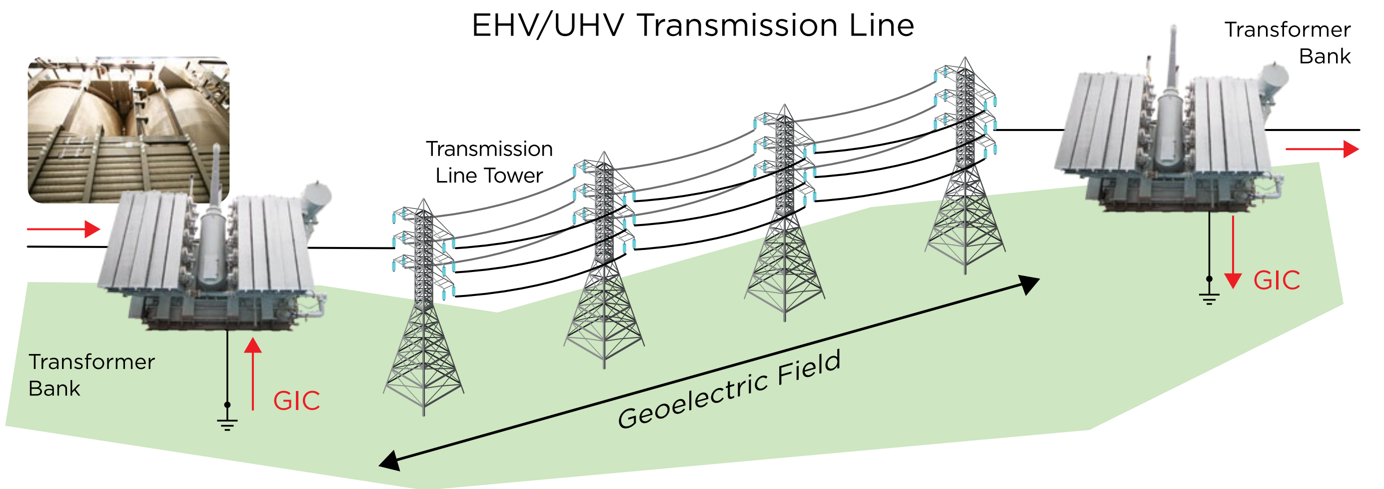


Figure 3. GIC flow in power network.

Some of the critical effects that GICs have on Power Transformers are:

- Heating of metallic components (for instance: tank walls, clamps, tie plates)
- Increase of reactive power demand, which leads to a possible voltage collapse
- Harmonic content in currents (even and odd harmonics), which causes false tripping of relay protection devices

Typical GIC profiles are characterized by pulses up to 300Amps/Neutral with short durations of 2 to 5 minutes or low magnitudes lasting hours.

Considering the duration of the above mentioned GIC profiles, less critical effects are:

- Acoustic noise
- Losses and temperature of core

IS EVERY TRANSMISSION TRANSFORMER AT RISK TO GICs?

Not exactly, the effects of variations in the geomagnetic field are critical in latitudes of +/- 40, territories like Canada or the United States are the ones mainly affected in the American continent. In addition, grounded transmission networks with high voltage levels, equal to or greater than 200 kV, are the most susceptible because the separation between grounded transformers is enough for the GICs to reach levels of hundreds of amps in a neutral conductor.

The greater the GMD, the greater the GICs magnitudes, which means more transformers are at risk!

Figure 4. During the Geomagnetic Storm of 1989, people were able to see the Aurora at much lower latitudes than during periods of solar quiescence. Credits: Roen Kelly, after American Geophysical Union.

According to the scale proposed by **NOAA** (National Oceanic and Atmospheric Administration), **G4** Scale storms can cause problems of voltage control in the Transmission networks, as well as incorrect protections allowing the risk of cascading event and possible "blackout", if not prepared.

SCALE	EFFECT	PHYSICAL MEASURE / AVERAGE FREQUENCY (1 cycle = 11 years)
EXTREME G5	**POWER SYSTEMS** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collpase or blackouts. Transformers may result damaged. **SPACECRAFT OPERATIONS** Spacecrafts may experience extensive surface charging, issues with orientation, uplink/downlink and tracking of satellites. **OTHER SYSTEMS** Pipeline currents can reach hundreds of amps, HF (high frecuency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and Aurora has seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9 4 per cycle (4 days per cycle)
SEVERE G4	**POWER SYSTEMS** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **SPACECRAFT OPERATIONS** Spacecrafts may experience extensive surface charging and tracking issues, corrections may be needed to fix orientation issues. **OTHER SYSTEMS** Induced pipelines current affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and Aurora may be seen in areas like Alabama and north California (typically at a 45° geomagnetic lat.).	Kp = 8, including a 9. 100 per cycle (60 days per cycle)
STRONG G3	**POWER SYSTEMS** Voltage corrections may be required, false alarms may go off on some protection devices. **SPACECRAFT OPERATIONS** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation issues. **OTHER SYSTEMS** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and Aurora may be seen in areas like Illinois an Oregon (typically at a 50° geomagnetic lat.).	Kp = 7 200 per cylce (130 days per cycle)
MODERATE G2	**POWER SYSTEMS** High-latitude power systems may experience voltage alarms, long-duration storms may result in transformer damage. **SPACECRAFT OPERATIONS** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **OTHER SYSTEMS** HF radio propagation can be fade at higher latitudes, and Aurora may be seen in areas like New York and Idaho (typically at a 55° geomagnetic lat.).	Kp = 6 600 per cylce (360 days per cycle)
MINOR G1	**POWER SYSTEMS** Weak power grid fluctuations can occur. **SPACECRAFT OPERATIONS** Minor impact on satellite operations may be experienced. **OTHER SYSTEMS** Migratory animals may be affected at this and higher levels; Aurora may be commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5 1700 per cylce (900 days per cycle)

NOAA space weather scales.

WHY SHOULD TRANSMISSION TRANSFORMER AND GENERATOR OWNERS CARE ABOUT GICs?

TPL-007-1 is a regulation developed by NERC (North American Electric Reliability Corporation) and implemented by FERC (Federal Energy Regulatory Commission). TPL007-1 establishes that planning coordinators, transmission planners and owners of EHV transformers are required to conduct assessments every five years in order to determine the impact a Geomagnetic Disturbance event may have had on their equipment, and, in this way, guarantee grid stability.

Two type of assessments are required:

- Vulnerability assessment of the Grid
- Transformer Thermal Impact assessment

Should the system fail to comply with the performance requirements, a Corrective Action Plan (CAP) must be developed in order to make sure all performance requirements are duly met.

Prolec GE developed a GIC Resistant Transformer that meets the guidelines described on the C57.163 IEEE Guide. In order to ensure the capability of transformers while under a GMD event stays intact, critical components must be specially taken care of during the Design Stage.

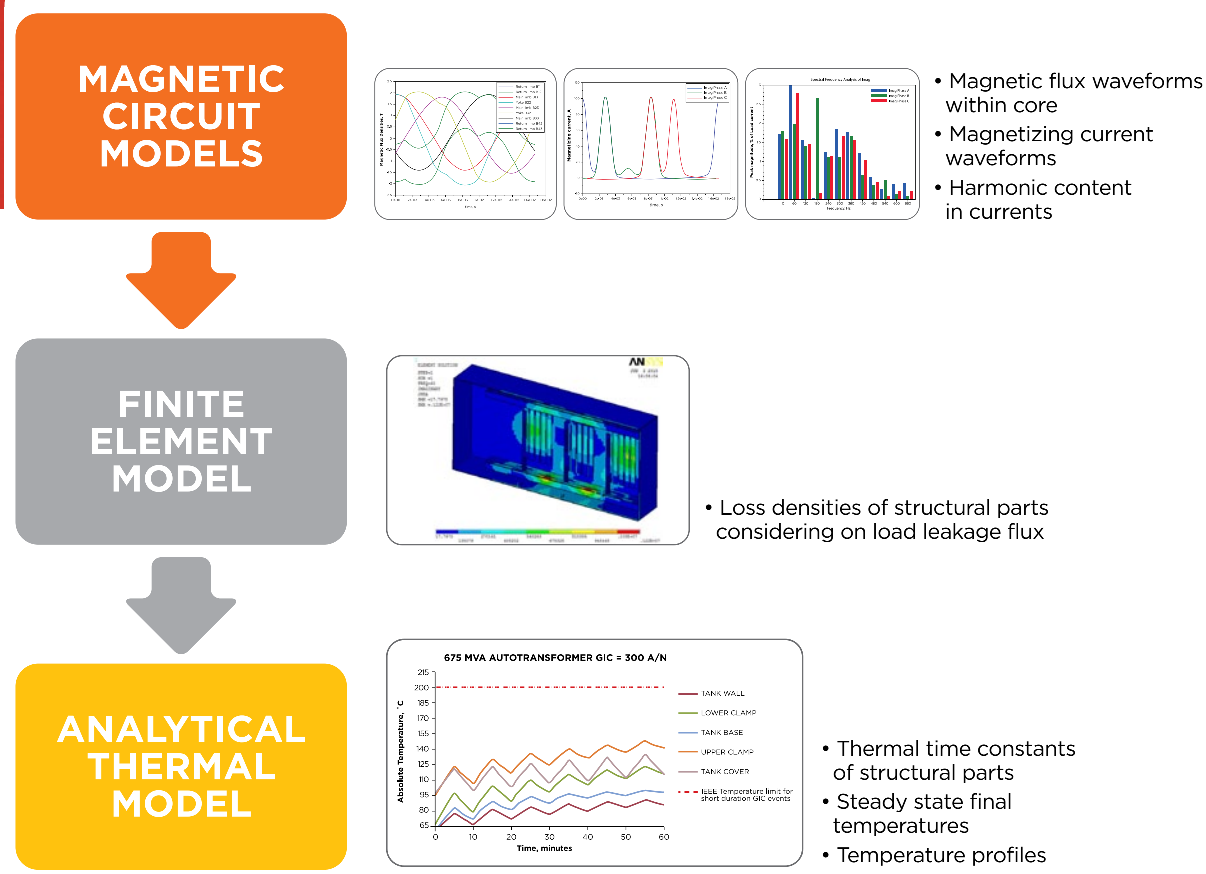
Transient models have made possible to design transformers able to withstand GIC pulses while complying with the recommended thermal limits and guaranteeing transformer reliability.

Prolec GE has developed mathematical models designed to comply with IEEE C57.163 and provide information required to conduct a power system stability assessment as required by Reliability Standard TPL-007-1.

As part of the process followed by **Prolec GE**, GIC Magnitudes and Electrical/ Magnetic Designs are required to be used as input for the complete assessment; **Prolec GE** has developed magnetic models for different core topologies, being able to determine the following with these models:

- Magnetic flux waveforms within core
- Magnetizing current waveforms
- Harmonic frequency spectrum in currents

These results have been used as a baseline on how GIC may impact the integrity of transformers during their life cycle. Finite Element and thermal models are used to analyze losses in metallic components. This analysis provides us with temperature profiles, which, based on the results obtained, help us decide what changes need to be implemented during the Design Process.



References:

[1] National Aeronautics and Space Administration, "What is the solar cycle" [online]. nasa.gov, 2009, [Consulted October 14,2019], Available on: https://spaceplace.nasa.gov/solar-cycles/en/

[2] National Aeronautics and Space Administration, "The Day the Sun Brought Darkness" [online]. nasa.gov, 2019, [Consulted October 14,2019], Available on: https://www.nasa.gov/topics/earth/features/sun_darkness.html

[3] National Aeronautics and Space Administration Article, "Earth's Pulsating Ionosphere" [online]. nasa.gov, 2016, [Consulted October 14,2019], Available on: https://www.nasa.gov/image-feature/goddard/2016/earths-pulsating-ionosphere

[4] National Aeronautics and Space Administration, "Earth's Atmospheric Layers" [online]. nasa.gov, 2013, [Consulted October 14,2019], Available on: https://www.nasa.gov/mission_pages/sunearth/science/atmosphere-layers2.html

[5] National Oceanic and Atmospheric Administration (NOAA), "NOAA Space Weather Scales" [online], swpc.noaa.gov, [Consulted October 14,2019], Available on: https://www.swpc.noaa.gov/noaa-scales-explanation

[6] IEEE Std. C57.163-2015 "Guide to establish the capability of transformers while under GMD event", Sponsored by Transformers Committee, IEEE Power and Energy Society

[7] Reliability Standard TPL-007-1, Transmission System Planned Performance During Geomagnetic Disturbances developed by North American Electric Reliability Corporation (NERC) in response to Federal Energy Regulatory Commission (FERC) order.

[8] Figure 3 / Reference: C57.163 IEEE Guide for Establishing power transformer capability while under GICs.

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