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## Geomagnetically Induced Currents

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### Definition

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| Geomagnetically induced current (GIC) | Intense, low-frequency, quasi-direct currents flowing in the conductor systems owing to rapid changes of the geomagnetic fields |
| Space weather | Dynamic variations at the Sun and in interplanetary space disturbing the near-Earth space environment creating conditions that are hostile to space-borne and ground-based technological systems and can even impose danger to human life |

### Introduction

Geomagnetically induced currents (GICs) are intense, low-frequency (~0.001–1 Hz) currents flowing in Earth-ground conductor systems owing to rapid changes of the geomagnetic fields (dB/dt $>$ 1 nT s$^{-1}$) (Campbell 1980; Akasofu and Aspnes 1982). According to Faraday's law of induction, a fluctuating geomagnetic field induces geoelectric fields which drive GICs in the ground and electrical power systems. The induced currents are essentially quasi-DC as their frequencies are much less than the frequency of the electrical grids operating at 50 or 60 Hz.

Intense GICs are known to cause extensive and expensive damages to a variety of technological systems such as electric power systems, telecommunication cables, and natural gas pipelines. Strong GICs enter the neutral grounding of transformers (operating typically at ~50 Hz frequency) causing transformer core magnetic flux increase and consequent half-cycle saturation of the core. These in turn distort the AC waveform of the power signal, which can lead to transformer overheating, system-relay interference, reactive power loss, or even system damage.

### Space Weather Events and Geomagnetically Induced Currents

Space weather generally refers to the physical conditions in the Sun-Earth system that can affect the performance of spacecraft and ground-based technological systems, including electric power distribution systems. The solar sources of the space weather are the solar activity transients such as solar flares and coronal mass ejections (CMEs), solar wind high-speed (~550–800 km s$^{-1}$) streams (HSSs), and corotating interaction regions (CIRs) formed by the HSS interaction with slow (~300–400 km s$^{-1}$) solar-wind streams. During all of the above phenomena, significant variability occurs in the solar-wind speed, plasma density, and strength and direction of the magnetic field. The dynamics of geospace, extending from the Earth's plasma environment called the ionosphere to the protecting magnetic bubble called the magnetosphere, is largely affected by this solar-wind variability.

Magnetic reconnection between the interplanetary magnetic field (IMF) and the dayside geomagnetic field is considered to be the main mechanism of energy transfer from solar wind to the Earth's magnetosphere (Dungey 1961). The process of magnetic reconnection works most efficiently when IMF is directed southward, opposite to the dayside magnetopause magnetic field direction (Tsurutani and Gonzalez 1997). Dayside magnetic reconnection leads to injection and storage of solar wind kinetic energy (energetic particles) in the magnetotail. This causes stretching of the magnetotail and formation of a near-Earth neutral line. Onset of magnetic


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reconnection at this neutral line gives rise to an explosive release of energy from the magnetotail toward the inner magnetosphere. This near-midnight plasma injection excites a substorm (Tsurutani and Meng 1972), and auroras in the high-latitude nightside ionospheric region. If the southward IMF is intense with hours duration, such as during the magnetic cloud portion of an interplanetary coronal mass ejection (ICME) (Burlaga et al. 1981), the plasma injection is deeper and the particles get energized to ~10–300 keV. This leads to intensification of the ring current which produces a diamagnetic decrease in the Earth's magnetic field measured at near-equatorial magnetic stations. This latter effect is the *main phase* of the geomagnetic storm. After the storm main phase is over, the decay of the ring current starts the *recovery phase* of the magnetic storm. The energetic particles are lost by several physical processes, namely, charge-exchange, Coulomb collisions, wave-particle interactions, and convection out the front side of the magnetopause (Kozyra and Liemohn 2003).

The intensity of the magnetic storm is measured by the disturbance storm time (Dst) index, an hourly geomagnetic activity index, or by the SYM-H index with a temporal resolution of 1 min. The intensity of a substorm is measured by the auroral electrojet (AE) index. The intensities of both substorms and magnetic storms are expressed in nT. During intense magnetic storms, near-equatorial magnetic field disturbances of a few 100s nT are recorded for a few hours to days. This ground magnetic effect is due to the magnetospheric ring current which exists from $L = 2$ to $L = 8$ (L is the distance in Earth's radius $R_E$ that a dipole magnetic field crosses the magnetic equator). During super magnetic storms, the magnetic disturbances could be higher, exceeding 1000 nT at times. Substorms cause high-latitude ground-magnetic disturbances from ~100 to 1000s nT lasting for a few minutes to hours. These magnetic effects are due to a combination of the auroral electrojet which is located in the ionosphere at a height of ~100 km and field-aligned currents coming from the magnetosphere to the ionosphere. The ring current effects of substorms are relatively minor compared to that of magnetic storms. During magnetic storm main phases, many substorms may also occur.

A second means of energy transfer from the solar wind to the magnetosphere is sudden solar wind ram pressure changes. One mechanism is the pressure pulse due to high plasma densities sunward of fast magnetosonic shocks (Kennel et al. 1985). These cause sudden impulses ($SI^+$s), strong changes of the equatorial magnetic field of 10–100 nT with ~1–10 min durations (Araki 1977), the triggering of nightside substorms (Heppner 1955), and in extreme cases, the formation of new radiation belts (Blake et al. 1992).

Geomagnetic field disturbances associated with magnetic storms and substorms are known as the key factor for the generation of GICs. Strongest GIC events are recorded in the high (>50°) geomagnetic latitude zone in association with large amplitude magnetic field fluctuations during intense and frequent auroral activities (Pirjola 2000). However, recent studies show evidence of mid-to-low latitude GICs in association with $SI^+$ events caused by solar wind ram pressure impingement on the dayside magnetopause of the Earth (Gaunt 2014; Carter et al. 2015).

## Generation of GIC Events

A GIC event is generated by the high-frequency changes in geomagnetic fields due to space weather events. Geomagnetic storms, substorms, supersubstorms, magnetic pulsations, and sudden impulses ($SI^+$) are the major drivers for the generation of GICs (Pulkkinen et al. 2005; Viljanen et al. 2006; Ngwira et al. 2014; Tsurutani et al. 2020). In fact, a GIC event is essentially the ground manifestation of the complex space-weather chain starting from the solar eruptions, extending to the interplanetary space, and then to the surface of the Earth and below. Therefore, the GIC signals carry information about the processes involved in the Sun-Earth connection and space weather. Most models calculate GIC either from the measurements of geomagnetic field (B) and its time derivative dB/dt using magnetometers or from the magnetotelluric measurements of both B field and electric field E (Gaunt 2016; Pulkkinen et al. 2017).

Systematic studies on GICs and their effects on the electric power systems were started first in the high-latitude countries, e.g., Finland (Viljanen and Pirjola 1994) and Canada (Boteler 2001), where GICs might be expected to occur. Later, the GIC studies have been undertaken in the low- and mid-latitude regions such as Scotland, China, Japan, South Africa, Brazil, New Zealand, and Australia. An excellent overview of GIC impacts on electrical power systems is given by Gaunt (2016). Direct current (DC) blocking devices, such as neutral-point reactors and series capacitors, are being designed and installed in high voltage transmission grids to mitigate the flow of GICs through transformers (Kappenman et al. 1991; Thomson et al. 2010). The real-time monitoring of GICs provides a useful means to understand the power-system status, but it does not guarantee that the system will survive a future severe GIC event (Erinmez et al. 2002). At present, no reliable forecastable model for GICs exists (Gaunt 2016).

The severity of the GICs flowing through ground-based technological systems depends on several factors such as severity of the magnetic disturbances in the magnetosphere-ionosphere system, location and configuration of the system (i.e., power transformers, transmission lines, etc.), and conductivity of the Earth's surface and interior, coastal effects, etc. (Clilverd et al. 2018; Liu et al. 2018). The highest GIC levels occur for the fastest rate of change of the magnetic field. Therefore, dB/dt is considered as an important parameter to quantify the relative level of GIC threat. For example, the Québec power station blackout during the 13–14 March 1989 magnetic superstorm occurred when the peak dB/dt was ~480 nT/min. Recent study of the March 1989 magnetic storm by Boteler (2019) shows that the peak dB/dt occurred during a shock-induced substorm, much before this superstorm attained its peak Dst = −589 nT value. It is interesting to note that dB/dt values exceeding 2000 nT/min have been observed, and much higher values ~5000 nT/min might have occurred during historic magnetic storms (Kappenman 2006). Recent studies show that compression of the magnetosphere caused by interplanetary shock impacts, discussed earlier, increases the magnetopause currents leading to large dB/dt variations in the mid- to low- latitudes as well as in the equatorial electrojets (Carter et al. 2015; Oliveira et al. 2018). Furthermore, in many magnetic storms, the GICs due to the $SI^+$ can be much larger than those recorded at the same station during the storm main phase (Zhang et al. 2015). Thus, even the power stations situated near the equatorial electrojet are susceptible to GIC risks. For maximum possible dB/dt values due to $SI^+$s, we refer the reader to Tsurutani and Lakhina (2014).

## Future Outlook

Impacts of GICs on electric power systems, natural gas pipelines, and telecommunications have direct socioeconomic impacts. This can be understood from some historical examples of large GIC events. The largest recorded magnetic storm at Earth with a peak Dst = −1760 nT was caused by a CME associated with an extremely intense solar flare on 1 September 1859 (Tsurutani et al. 2003). GICs on telegraph lines caused arcing that led to fires and electrical shocks (Loomis 1861). Two recent examples of GIC-related hazards are the collapse of the entire Hydro Québec power system during a superstorm (with peak Dst = −589 nT) on 13–14 March 1989 (Allen et al. 1989), and the transformer collapse near Malmö in Sweden during the 29–30 October 2003 superstorm (with peak Dst ~ −400 nT) (Pulkkinen et al. 2005; Wik et al. 2008). Due to growing dependence of modern society on electric technology (and greater vulnerability), large GIC impacts are now realized to be quite damaging to society as they can disrupt functioning of the power grids and communication cables, and cause erosion of oil and gas pipelines (Royal Academy of Engineering report 2013; Pulkkinen et al. 2017). Currently GICs are considered as the greatest space-weather hazard globally.

There has been tremendous progress in understanding the space weather processes and generation of GICs during the past two decades. An exhaustive review on the current status and future challenges of space-weather physics and solar-terrestrial physics (STP) is given by Tsurutani et al. (2020). The ultimate challenge for the space community is to predict the occurrence of extreme magnetic storms and their associated extreme GICs. Although extreme events are rare, yet they are the ones that can cause the maximum damage. Presently, there is a limited understanding of the upper limit for the geoelectric fields that drive GICs. Additionally, the prediction of GICs with a lead time of 1–3 days is very limited or unreliable (Gaunt 2016; Pulkkinen et al. 2017) as reliable estimates for the strength of magnetic storms a couple of days in advance are not available. The major sources of uncertainty are prediction of the IMF southward components associated with the ICME and in the sheath region behind the interplanetary shock. Solar wind measurements taken upstream of the Earth at the Lagrange 1 (L1) point by NASA's Advanced Composition Explorer (ACE) and Deep Space Climate ObserVatoRy (DSCOVR) are being used to provide reliable estimates on the solar-wind drivers. This information is used in the physics-based and empirical models to calculate the currents in the magnetosphere and ionosphere to make real-time prediction of GICs with a lead time of ~30 min or so. For extreme events, such short-time notice is not sufficient to put any mitigation plan in place against hazardous extreme GICs. Since GICs depend on the ground conductivity and characteristics of regional power grids, it is a big challenge for the modelers to develop global GIC models that can predict the magnitude and duration of GIC events in different parts of the world.

## Cross-References

- ▶ Electromagnetic Induction
- ▶ Electromagnetic Pulsations and Magnetic Storms
- ▶ Extreme Events
- ▶ Magnetotellurics
- ▶ Space Weather

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