The magnetic storms that flare up on the surface of the sun are known to afflict electric power systems with everything from minor upsets to major outages. In one extreme case, in March 1989, such a geomagnetic disturbance took down the entire Hydro-Québec power grid, leaving six million customers in the Canadian province without electricity for 9 hours, and also knocked out power stations in the Northeastern United States. That disturbance occurred at one peak of an 11-year solar cycle, the 22nd to be recorded since soon after the mysterious ebbing and flowing of sunspots first was recognized in the 17th century.

Sunspots, or solar storms, are basically magnetic field lines looping out of and into the sun [photograph below]. Their appearance often is associated with the discharge of huge amounts of matter, called coronal mass ejections, consisting mostly of ionized hydrogen and helium. The ejections, about a million degrees Celsius at the surface of the sun, appear as bursts in the otherwise rather steady flood of ions and subatomic particles moving toward the earth—the solar wind—at a velocity of about 450 km/s . The interaction of those particles with the earth's magnetosphere kindles the spectacular auroras seen periodically in the polar regions.

TOM S. MOLINSKI
Manitoba Hydro

WILLIAM E. FEERO
Electric Research Inc.

BEN L. DAMSKY
Electric Power
Research Institute

Shielding grids from
solar storms

Geomagnetic disturbances are a real danger to some grids— being prepared for one requires assessment of local conditions, as well as monitoring and warning systems

The full solar cycle consists of two half-periods of 11 years each, demarcated by reversals of the sun's polarity. During one half-cycle, sunspots are in alignment with the earth's magnetic field; in the other, they are antiparallel. Peaks in storminess occur midway through the half-cycles and are somewhat more severe during the odd-numbered 11-year periods, possibly because the sunspots' alignment opposes the earth's field. The last such peak brought on the 1989 power breakdown; the next just began and coincides roughly with the publication of this article—it could last two more years. While the present cycle shows signs of being slightly less severe than the last, the long-term trend seems to be toward greater solar storminess.

As seen in 1989, geomagnetic disturbances can be disruptive as well as glamorous. The high-altitude currents induce mirror currents in the earth, as well as in the parallel paths provided by such man-made systems as telephone lines, pipe lines, railways, and transmission lines. In turn, these geomagnetic disturbances affect radio communication systems, satellite operations, and electric power grids.

So how well prepared are power systems to deal with this sort of disruption, compared with 11 years ago? The picture is complex and mixed. Certainly a much more elaborate space-based infrastructure for issuing some warning of solar storms exists today, and some progress has been made in developing scales to assess their violence. Even with warning times as short as a half-hour, much can be done.

But if warning times are better, power systems also are more vulnerable to solar disruption because of a growing worldwide tendency to move large quantities of electricity over long transmission lines. Of necessity, remedies must be local and regional. Vulnerability to solar activity is mainly a function of geographical latitude and locality, putting the main burden of preparedness on the individual utility. And readiness appears to vary widely among those utilities that could be most affected by the ongoing cycle of storms.

RISK FACTORS

The basic nature of the problem is not hard to grasp. Geomagnetically induced currents (GICs) caused by solar activity typically flow into and out of the power grid through various ground points [see p. 59.] The driving force is the voltage induced in the transmission lines themselves both by the ionospheric current and by the earth current. Although the GIC fluctuates, it can be categorized as a quasi-direct current, since the variations in flow are at frequencies well below 1 Hz. Currents have been measured in a single transformer neutral in excess of 184 A in North America and 200 A in Finland.

Severe GIC events often persist for several hours, and in a major storm, currents may recur for several days, either regionally or continentwide. But the period of a large flow with the same polarity seldom lasts for more than a few minutes.
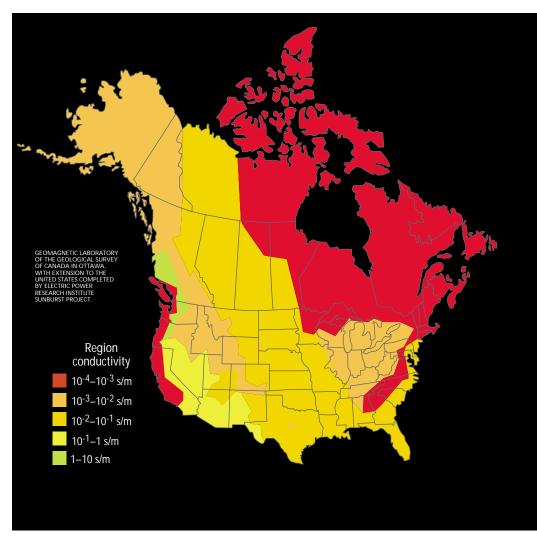
Two sets of factors determine the severity of a GIC event for an electric utility. One set is associated with the planet's surface horizontal geoelectric field, or rather, with its extent and intensity. The other has to do with the type of equipment used and the way in which it is deployed.

The field's extent and complexity depend not only on ionospheric currents, but also on the earth's conductivity and how near the power system is to the polar auroral zone. As a function of location and depth, the earth's conductivity varies by as much as five orders of magnitude [Fig. 1, left]. The geoelectric field is largest in areas of high earth resistivity near the auroral zone. In North America, for instance, the zone extends from 55 to 70 degrees latitude.

Suppose a severe geoelectric event is one in which the change of magnetic field per unit time (dB/dt) is greater than 300 nanoteslas per minute. Then its probability of occurrence over a whole 22-year solar cycle ranges from two-tenths of a percent for any unit time in northern latitudes to two-thousandths of a percent in, for example, the southern regions of the United States [Fig. 1, right].

Note that coastal areas are especially susceptible to GICs. The induced current flowing in the ocean prefers (so to speak) to enter the power system neutrals in east-west running lines rather than the more highly resistive land. The effect is enhanced by charge accumulation at the coast, due to the earth's higher resistivity relative to water.

Note also that severe storms can occur at any time during the

GEOMAGNETIC LABORATORY OF THE GEOLOGICAL SURVEY OF CANADA IN OTTAWA, WITH EXTENSION TO THE UNITED STATES COMPLETED BY ELECTRIC POWER RESEARCH INSTITUTE SUNBURST PROJECT.

Region conductivity

10^{-4}–10^{-3} s/m

10^{-3}–10^{-2} s/m

10^{-2}–10^{-1} s/m

10^{-1}–1 s/m

1–10 s/m

solar cycle. Still, they are more likely—probably much more likely—to occur near the peaks.

Even so, the danger of a power system suffering catastrophic effects (outages or damage) from GICs is modest compared to other hazards. Most utilities in North America design their physical infrastructures to withstand any wind storms or ice loadings except for a worst-case event—expected to happen no more often than once every 50 years. The risk of catastrophic damage or an outage in any given grid system from GICs probably is much smaller than that. What is more, damage incurred from a severe terrestrial storm would generally be more costly and difficult to repair.

SUSCEPTIBILITY OF EQUIPMENT TYPES

How electrical equipment is affected by GICs ultimately is a function of the equipment itself and the way it is deployed. Key factors include the orientation of the transmission lines (north-south vs. east-west); their lengths; the electrical dc resistance of the transmission conductors and transformer windings; the transformer type and mode of connection; and the method of station grounding and resistance.

The main reason power systems are increasingly likely to fall victim to GICs is that as electricity is traded over greater distances, the longer transmission lines are exposed to larger induced voltages (usually in the range of 1–6 V/km), driving larger GICs. The vulnerability of transmission networks to GICs today in North America is consequently much greater—perhaps by a factor of two or three—than 20 years ago. Since few new transmission lines have been built in recent years and electricity transfers over existing lines are much heavier, the probability of a large storm coinciding with heavy flow is much higher.

Statistically, the largest component of ionospheric-induced geo-electric fields runs east-west, and most major transmission lines have some east-west component. Long lines usually require voltage support devices like capacitor banks or static volt-ampere reactive (VAR) compensators, used to make up for reactive line losses. (Reactive power, measured in VAR, represents energy stored in electric or magnetic fields and is consumed or absorbed in the magnetic fields of inductive equipment.) Capacitors and VAR compensators may be prematurely tripped because their protective relays respond to harmonics created by transformer half-cycle saturation.

Half-cycle saturation occurs when the transformer flux is offset by the quasi-dc nature of the geomagnetically induced current, forcing the transformer to operate in the nonlinear region of the saturation curve for half of every cycle. VAR consumption thereupon soars and a complete harmonic current spectrum is produced, with potential cascading effects on other system components.

Because the transformer core is now loaded beyond its capacity, stray eddy currents outside it also can melt or otherwise damage materials in the transformer itself. In the 1989 solar storm, GICs destroyed a massive step-up transformer associated with a 1000-MW nuclear power plant in the eastern United States. Adding insult to injury, when the utility asked the supplier for a replacement, it was told its order would receive top priority but still take almost two years to fill.
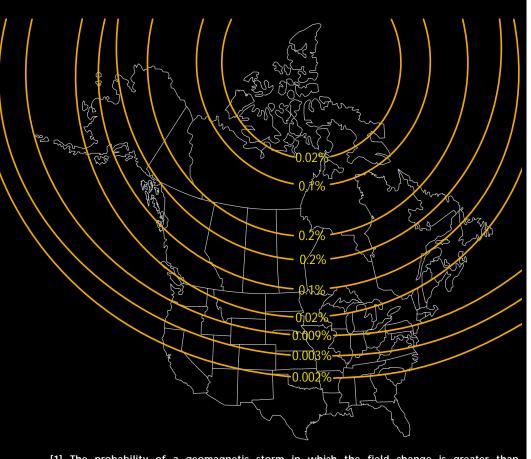
From the 1960s to the 1980s, a relatively quiet period of solar storm activity lulled some electrical utilities and equipment manufacturers into neglecting to GIC-harden their apparatus. In their defense, let it be said, it is very hard to redesign some equipment, such as power transformers, to be more immune to the effects of GICs. Moreover, the large transformers associated with the transmission lines are usually made up of three single-phase units, as these are easier to ship and cheaper to stockpile; but they are more susceptible to GIC than three-phase units, in which GIC effects are partially canceled. Relay design modifications, on the other hand, could easily be made to improve response during geomagnetic events; less forgivably, relay manufacturers have been slow to recognize the opportunity.

TRANSFORMER EFFECTS

The most important effects of GICs are those related to their impact on large power transformers [Fig. 2]. Transformer half-cycle saturation, either directly or indirectly, is responsible for most other ill effects on power systems or power system apparatus.

During half-cycle saturation, most of the excess flux is external to the core, flowing through adjacent paths such as the tank and clamps. The external flux produces eddy currents and localized

[1] The probability of a geomagnetic storm in which the field change is greater than 300 nanoteslas per minute can be as high as 0.2 percent per unit time [right]. But the impact of the storm on a power system depends on the earth's local resistivity [left, in siemens per meter].

tank wall hot spots, with temperatures as high as 175 °C recorded. To date, no one has conducted adequate computer simulation studies modeling transformer heating by GICs. But it stands to reason that repeated exposure to GIC-related heating would progressively damage the transformer winding insulation, whose short-livedness may cause premature transformer failure.

Unfortunately, linking these effects is hard because most utilities do not have extensive databases of GIC occurrences. As a result, a transformer failure may be misdiagnosed. Only a few known failures of power transformers can be directly linked to GIC, one being the 1989 disaster in the Northeastern United States.

While GIC cannot flow in large turbine generators because of the delta-wye step-up transformer connected to the generator [Fig. 3], the generator is still subject to the harmonics caused by transformer half-cycle saturation. The second and fourth harmonics, which couple readily with the generator rotor circuit, are among the largest harmonics produced during a strong geomagnetic disturbance. They can overheat the rotor end rings, while the positive sequence harmonics could give rise to mechanical vibrations.

(Sequence components are the result of a transformation of variables so as to convert the power systems' complex, coupled, three-phase circuit equations into three simple circuit representations called positive sequence, negative sequence, and zero sequence. This transformation was developed over 80 years ago and the use of sequence components has become the normal means of analyzing, monitoring, and detecting abnormal conditions on the power systems.)

Because these rotor-heating currents increase linearly with larger GIC in the step-up transformer neutral, care must be taken to ensure that protection remains adequate throughout. Hampering this effort is the fact that there are no standards for permissible harmonic currents into generators, plus the fact that conventional negative-sequence relays for generators may be designed to respond only to fundamental frequency.

Some digital relays used today are also sensitive to harmonics, in that they measure the peak value of the current and then calculate the rms current on the basis of a 50-Hz or 60-Hz waveform. Owing to the increased harmonics from transformer half-cycle saturation, these digital relays react to as little as one-half the current desired, causing false trips of equipment such as shunt capacitor banks, filter banks, and static VAR compensators.

Transformer neutral overcurrent relays also may operate incorrectly since the triplen harmonics (3rd, 6th, and so on) can appear as zero sequence currents and provide a "false" large neutral current to the relay.

Under normal operating conditions, voltages and currents are for the most part positive sequence. But under abnormal conditions, of the kind created by short circuits or GIC-caused harmonic flows, negative and zero sequence currents and voltages will also exist. Because of the nature of three-phase systems, positive and negative sequence components cancel in the neutral paths of these circuits.

However, zero sequence quantities add in the neutrals. When half-cycle saturation occurs in all three phases, as it does under GIC conditions, it can be shown that the 2nd harmonics are negative sequence, the 3rd (and all triplen) harmonics are zero sequence, the 4th are positive sequence, the 5th are again negative, and so on.

Negative and zero sequence currents are commonly used in other protective relay schemes as well. In older relaying schemes, analog filters were used to extract the desired sequence component. It is then necessary to know the frequency response of these filters, because in some cases it may or may not be desirable to respond to the harmonic sequence components. For example, some directional schemes that utilize the negative sequence components may false-operate owing to the presence of the higher-order negative sequence harmonics. In addition, generator negative sequence protection may not respond when it should to the higher-order negative sequence harmonics.

Besides any direct effects of GICs on electric system components, operation of electric grids depends on communications that in theory also can be negatively affected by GIC. While there have been no proven GIC effects degrading the performance of protective relaying communications, this may be an emerging area of concern for utilities.

VOLTAGE COLLAPSE

In the extreme case, the combined half-cycle saturation effects of many transformers could lead to voltage collapse. The capability of the ac transmission system may decrease considerably when GIC increases because reactive VARs, needed for voltage support, are being consumed.

The consequent reduction in system voltage also tends to reduce stability margins, both transient and dynamic. This problem is greatly aggravated if voltage support capacitor banks or static VAR compensators are tripped off-line by the effects of excessive harmonics. Should even one or two large generators simultaneously be tripped on negative sequence, large areas of the network could go black.

Today's interconnected systems now span large geographical areas that can be simultaneously affected by VAR shortages, especially during heavy system loading. As many areas have not built new transmission lines for over a decade, this problem has worsened since the last solar peak. Obviously, because such systemwide blackouts are possible, it would be useful to be warned well in advance of solar disturbances likely to induce strong currents on earth. Yet at present no truly satisfactory indices relating to the severity of geomagnetic disturbances to GICs are routinely provided.

In 1999, the U.S. National Oceanic and Atmospheric Administration (NOAA) published a five-level G index that is intended to relate the effects of geomagnetic disturbances to scales
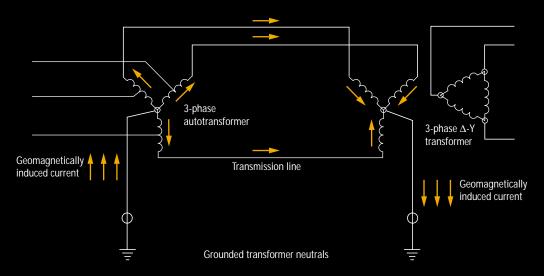

[2] Geomagnetically induced current (GIC) caused highly localized, although severe, damage to this large step-up transformer in a mid-Atlantic U.S. state in 1989.

From left to right, the tan-colored paper on the upper winding is intact but burned out below. Next, paper is completely burned out to the right but not left. Last, copper strands have melted.

[3] In this standard transmission line setup, geomagnetically induced current (GIC) flows from the earth into the grounded neutral of a three-phase autotransformer, where it divides evenly in each phase of the transformer. It then proceeds into the transmission lines and flows to other transformers, returning from them to earth. Note that an autotransformer—one in which windings are shared—permits GIC to pass through, while a delta-wye transformer does not.

similar to those used for weather. While the new scale has a certain user-friendly resemblance to scales used for hurricanes, it is identical in substance—if not in terms of where the lines are drawn—to one of the two indexes already used to gauge the severity of these disturbances, the K scale.

SCALING GEOMAGNETIC DISTURBANCES

Before NOAA's issuance of the G scale at the end of last year, the K index and the A_k index helped in classifying the intensity of geomagnetic disturbances. The K index ranges from 0 to 9 and is based on the maximum magnetic field variation over a 3-hour interval. The A_k index, in the 0–400 range, is a 24-hour index derived from eight daily 3-hour K indices. Values of K in the 0–4 range and of A_k in the 0–20 range represent quiet geomagnetic activity; and values of K of 5 or A_k in the 30–50 range represent a minor storm. A severe storm gives rise to K values in the 7–9 range, and A_k values in the 100–400 range.

Measurements of the variations of the earth's magnetic field are handled by several national agencies. These include NOAA's Space Environment Center in Boulder, Colo., Canada's Geological Survey in Ottawa, and the Finnish Meteorological Institute in Helsinki. Once the measurements are made, they are interpreted in terms of the A_k, K, or G scales, according to where they are measured on the planet's surface. Unfortunately, most of these scales also depend on averages over a fixed period of time—for example, 3 hours for the K indices—so they are reported after events are well under way.

The new G scale, based on the planetary K index (an average of readings from select global sites), is NOAA's attempt at a tool that quantifies the anticipated effect on physical systems. NOAA has issued guidance attributing G-scale levels to possible power-system effects. But of necessity those effects are greatly simplified, precise predictions being impossible to base solely on G-scale measurements.

In calculating GIC, the rate of change over time of the earth's magnetic field is an important factor. The main problem of using the G scale for electric utilities, therefore, is that it is only a measure of the total magnetic field deviation, in a 3-hour window. Statistically, to be sure, a larger deviation in magnetic field will tend to correlate with large rapid changes in the field. But large G, K, or A_k indices are not as such directly translatable into large GIC. In effect, none is a good predictor of how power systems will be affected.

This problem is further compounded because, as previously explained, the geological structure can greatly influence the electric field even when the magnetic field variation is uniform over a large area. As a result, the best electric utilities can do at present is to supplement various related GIC measurements and forecasts with these severity indices.

OTHER MONITORING PROGRAMS

Since the strength and even time deviation of geomagnetic disturbances cannot be mapped directly to induced currents in grids, it becomes advantageous to measure the GIC directly in transformer neutrals. The same holds true for measuring a power system's total harmonic distortion and abnormal reactive power flow.

Some utilities monitor just the GICs in selected transformer neutrals to determine if their local power system is being affected. In a few cases, the data is communicated to the utilities' control centers to decide if any mitigation is necessary. While far superior to ignoring the existence of GIC, this limited data can encourage under- or over-reactions.

Measuring the GIC alone is inadequate because different transformer core types will respond to it differently. For this reason, Electric Research Inc., in State College, Pa., with the sponsorship of the Electric Power Research Institute (EPRI), Palo Alto, Calif., developed a system to measure the harmonics in the currents and voltages—the Sunburst system. A dozen electric utilities are members of the consortium supporting Sunburst.

Recognizing the need to know the breadth, intensity, and localized transformer saturation impacts as they occur, Electric Research installed Sunburst, using near–real-time Internet links to the sites of every consortium member. With Sunburst, the GIC can be easily measured in a dc transformer transformer neutral with a Hall-effect current monitor. But the availability of dc current transformers for transmission line voltage ratings is limited and their installation difficult and costly, so they are not widely deployed.

The goal is to collect complete and reliable harmonic and VAR loading data. A typical monitoring installation involves the simultaneous measurement of the transformer high- and low-side phase currents (ac current only), the neutral current (both ac and dc), along with the ac bus voltages. These quantities are usually sampled every 1–10 seconds, depending on the severity and duration of the GIC event. The stored information is time-tagged (usually with a satellite clock), so that comparisons and analyses can be made from many monitoring sites for the same geomagnetic disturbance.

At Hydro-Québec, harmonic distortion level is measured by comparing successive voltage peaks, the goal being to detect an unbalanced voltage. Typically, the total harmonic distortion for voltage is less than 2.5 percent on most power systems, but has been as high as 30 percent during severe GIC events.

Really substantial improvements in forecasting are possible now, thanks to NASA's launching of the Advanced Composition Explorer (ACE) satellite in 1997. It provides previously unavailable data on the density, polarity, and velocity of the solar wind. At 1.6 million kilometers above the earth, much farther aloft than standard geostationary orbits, ACE is positioned at the so-called L1 libration point where the gravitational fields of the sun and earth are balanced. Orbiting as it does in a halo well above the earth's magnetosphere, which reaches about 160 000 km and higher, the satellite observes local particle and magnetic perturbations from outside the earth's magnetosphere.

From that vantage point, ACE gathers data that is input to a magnetospheric–ionospheric coupling model (still being worked on by researchers) to provide reliable advance warnings of geomagnetic disturbances. Warnings about large GICs are issued about a half-hour to an hour before they occur. The Sunburst Web site will present ACE data to members through a link with the NOAA/Space Environment Center Web site to alert the members to an impending event.

One private company already offers such forecasts. Others are working toward satisfying the power industry's alerting requirements. What is needed is to provide, in a form suitable for power systems, an accurate warning of an hour or more in advance of a storm, an estimate of its maximum severity, and when it is expected to end. (Worst-case storms may, however, allow only about a half-hour advance warning based on ACE data.)

Until confidence is gained in these predictive computer models, ground-based systems such as Sunburst, with its worldwide sites all reporting through the Internet, will give a near–real-time picture of the regions being affected and the intensity of the event at each location.

UTILITIES' MARCHING ORDERS

There is a lot utilities can do—and some things they cannot do.

For instance, series capacitors could be used to block the flow of GIC in transmission lines or neutral-blocking capacitors in transformer neutrals, but they are seldom used for this purpose because they are complicated devices, and to protect a typical power system completely, hundreds would be required. As this would be prohibitively expensive, most concerned utilities have opted instead to set up operating guidelines to cope with GIC.

Even establishing guidelines to mitigate harm done by GIC is no easy task. They must be related to the consequences of the level of GIC in the power system, which will vary from utility to utility.

Today few utilities as yet follow specific guidelines, the rest showing a lack of interest or resources or both. That said, about six utilities and two independent system operators (ISOs) in North America *do* follow some rather general rules, most of which are not rigorously derived. These guidelines are invoked to protect the security and stability of the power system.

For utilities to determine properly guidelines for what to do during GIC events, they must set up a process to be followed. This undertaking involves performing system studies to determine the grid's vulnerability to GIC effects. It must in addition include an evaluation of the risk of harmonic resonances and an assessment of the risk of system voltage collapse due to the shortage of VARs, as they are being consumed by the saturating transformers.

Other preparations should focus on determining the harmonic response of relays that may be affected (false or restrained operation) by GIC and the associated harmonics, so that appropriate fixes can be enacted. Wherever possible, it is best to choose transformers that are more immune to GIC (for example, three-phase, three-leg core design) and to design the power system to withstand larger voltage swings.

Generally, a utility can develop an appropriate mitigation strategy by collecting information from GIC monitors in the utility system and then following an organized approach in setting up operating guidelines. To help it get started, a team of experts in EPRI's Sunburst project has already identified the kind of monitoring program needed and developed a template for guideline development. This step-by-step procedure involves an analysis of the major power system components as they are affected by GIC or the related harmonics. ◆

ABOUT THE AUTHORS

Tom S. Molinski (M) is the supply-side enhancement engineer for Manitoba Hydro, where he is responsible for supply-side efficiency improvements, distributed generation evaluation, and non-utility generation procurement. He has also been Manitoba Hydro's representative on the Electric Power Research Institute's (EPRI'S) Sunburst research project since 1990 and chairman of the Sunburst utilities users group since 1994.

William E. Feero (F) was project manager for the Sunburst system from 1990 until 2000 at Electric Research Inc., State College, Pa. He has spent his career investigating transient phenomena and protection problems in electric power systems.

Ben L. Damsky (SM) is manager of power electronics systems in EPRI's Transmission and Substations Area, where he has served for 16 years. He also has worked on circuit breakers, monitoring, electronic media for maintenance, and silicon hexafluoride technology, and is the EPRI Sunburst project manager.

TO PROBE FURTHER

Information on geomagnetically induced currents (GICs) and geomagnetic storms can be found at the Electric Research Inc. Web site at http:// www.electric-research.com; the Canadian Geomagnetic Laboratory Web site at http://www.geolab.nrcan. gc.ca, and the National Oceanic and Atmospheric Administration's space environment center Web site at http://www.sec.noaa.gov.

A discussion and general explanation of GIC and its effects on power systems can be found in a paper by D.H. Boteler, R.J. Pijola, and H. Nevalinna, " The Effects of Geomagnetic Disturbances on Electrical Systems at the Earth's Surface," Advances in Space Research, Vol. 22, no. 1, 1998, pp. 17–27. Two other general overviews are a paper by T. Molinski, "Why Utilities Respect Geomagnetically Induced Currents," *Journal of Atmospheric Science and Terrestrial Physics*, special issue, fall 2000, forthcoming, and a paper by J.G. Kappenman, L.J. Zanetti, and W.J. Radesky, " Geomagnetic Storms Can Threaten Electric Power Grid," *Earth in Space*, Vol. 9, no. 7, March 1997, pp. 9–11.

Protective relaying requirements for capacitor banks, transformers, and generators exposed to GIC and harmonics from half-cycle saturation are comprehensively analyzed in a report by B. Bozoki, et al., "The Effect of GIC on Protective Relaying," *IEEE Transactions on Power Delivery*, Vol. 11, no. 2, April 1996, pp. 725–39.

A complete discussion of the various types of transformers, construction (core types), and resulting GIC effects can be found in a paper by W.J. McNutt on "The Effect of GIC on Power Transformers." *PES Special Publication 90th 0357–40PWR,* Geomagnetic Storm Cycle 22: Power System Problems on the Horizon, Power Engineering Society Summer Meeting 1990.