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The Effects of Solar Magnetic Activity on Electric Power Systems

JOHN C. SLOTHOWER AND VERNON D. ALBERTSON

ABSTRACT — Disturbances on large electric power transmission systems have been attributed to magnetic storms following solar flares. It can be shown that these magnetic disturbances are of the proper nature and magnitude to produce the documented effects on these electric systems. It is anticipated that these effects may become more serious with the greater and greater geographical spread of interconnected systems. More research and information on causal relationships is needed.

The facts that sun spots and other solar magnetic phenomena cause or at least influence the aurora borealis and have some sort of effect on long distance radio communication are widely known. Less generally known are the many other effects of such solar phenomena and the resultant fluctuations in the earth's magnetic field. Many of these "other effects" are very likely to become of increasing importance to electric utilities in their operation of large interconnected systems.

Past Effects on Power Systems

It has been noted for some time that large anomalous flows of both real and reactive power can take place in electric transmission systems during geomagnetic activity — the so-called "magnetic storms." These "storms" follow solar flares that are themselves rather violent magnetic disturbances on the surface of the sun and only rather vaguely related to the sun-spots. One of the earlier documented cases of solar effects on power systems occurred during the great magnetic storm of March 24, 1940, when disturbances on numerous electric systems in the northeastern part of the country were noted and measured.[3] The Philadelphia Electric Company experienced voltage surges and reactive power swings of 20% as well as the tripping of two large power transformers. Several large power transformers also tripped on the Central Maine Power Company's system where voltage dips of up to 8% were also experienced. The Ontario Hydroelectric Power Commission had numerous cases of difficulty involving the tripping of large power banks due to differential operations.

This same storm also produced wide swings in charging current on 22 Kv lines of the Eastern Massachusetts Electric Company and large reactive power swings on the Northern States Power Company system in Minnesota and Wisconsin. Still further, the Consolidated Edison Company experienced voltage disturbances and dips of up to 10% and a large increase in reactive power requirements.

Additional systems in the northeast also experienced voltage dips and other difficulties. These systems included Boston Edison, Niagara Hudson, and Public Service Electric and Gas of New Jersey. The immediate causes of the voltage dips were direct currents flowing in the windings of many distribution and substation transformers that produced varying degrees of saturation of the cores.

This same magnetic storm produced rather drastic differences in potential between the ends of various telephone company long-line cables. One 27-mile cable went off scale at 100 volts, and recurring swings were observed for the next two hours; 340 volts was measured on one 240-mile line a week after the main storm. A recording

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voltmeter went off-scale at 800 volts on a 140-mile telegraph cable and it is believed that the actual value may have been as high as 1500 volts. Hundreds of long-line circuits were completely out of service for hours at a time in the Northeast and upper Midwest.

Still another example of the terrestrial effects of solar magnetic activity occurred on September 22, 1957, when one of the Bureau of Reclamation's 230 Kv breakers at Jamestown, North Dakota, tripped because of abnormal currents flowing in the system that produced saturation of transformer cores and excessive 3rd harmonic currents in the ground relays.

One of the best-documented cases to date occurred following a solar flare on February 10, 1958. This particular storm was one of the most severe on record and its effects were more thoroughly recorded than those of earlier storms because of advance warning from solar and magnetic observatories. Occurring during the International Geophysical year, the storm was monitored by the extensive instrumentation that was available and "on duty." During this storm, Minnesota Power and Light Company experienced 15 Kv excursions on its 115 Kv transmission lines in northern Minnesota, and the Lake Superior District Power Company experienced abnormal neutral voltage shifts that caused a number of lightning arrester failures.

During this same magnetic storm, Northern States Power Company experienced highly erratic operation of both voltage regulators and load tap-changing equipment due to large fluctuations in both real and reactive power flow in its interconnections with the Bureau of Reclamation in western Minnesota. One large regulator operated 450 times during one 24-hour period when the normal would be possibly 40 operations. The load tap-changing equipment operated 300 times instead of its normal 30 in the same 24-hour period. A chart showing some of the abnormal power flows is shown in Figure 1.

Several rather interesting parallels may be seen in the cited examples of solar effects on electric utilities. The first is that all occurred in the more northerly portions of the country. A second and more significant parallel is that they all occurred about one day after a major solar flare. And, of course, all *can* be explained by assuming that geomagnetic disturbances were responsible.

Before we attempt an analysis of these events, let us take a look at just what this natural phenomenon is that is blamed for all this trouble! The "primordal cause" is some sort of electro-magnetic disturbance deep within

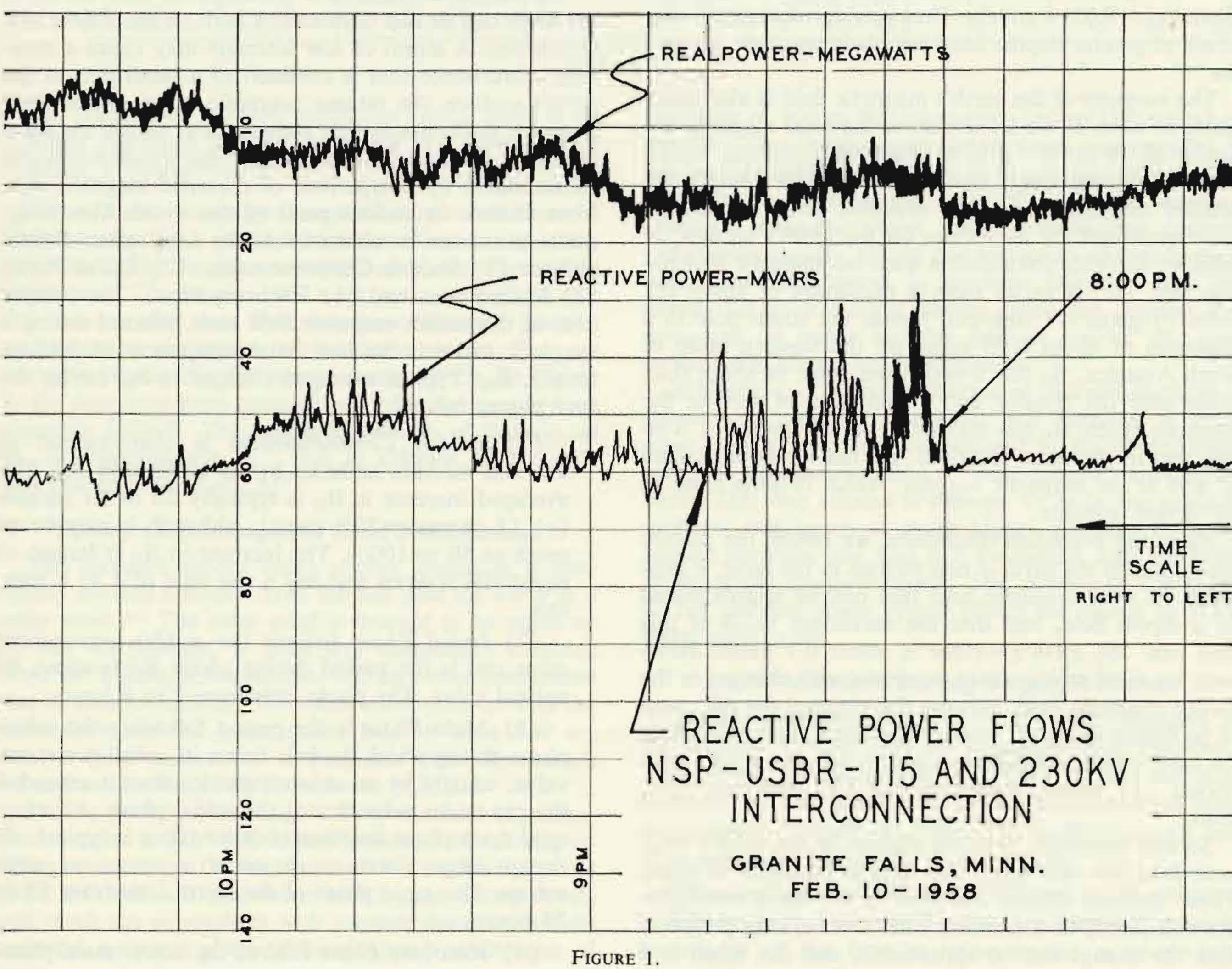

FIGURE 1.

the bowels of the sun itself. The mechanism of these disturbances is not at all well understood but the surface effect is what is known as a solar flare. It is this flare and its associated phenomena that affect the earth's magnetic field.

The Earth's Magnetic Field

We know, of course, that the earth possesses a magnetic field. While the true origin of the earth's magnetic field is not known even today, it has been measured and studied for hundreds of years. To a first approximation, the magnetic field of the earth is similar to that of a magnetic dipole located at the geographical center of the earth. There are local anomalies in the main dipole field that are due to induced and permanent magnetization of rocks in the earth's crust. As far as this paper is concerned, these local anomalies are of no importance and will be neglected.

Further, the earth as a whole exhibits nonferromagnetic properties, which is certainly true for the earth's crust, except for local deposits of ferrous materials in a relatively small number of locations. While the molten core of the earth may contain ferromagnetic substances, the Curie temperature for iron (approximately 750°C) is reached at a depth of 25 kilometers or 15.5 miles (1 kilometer = 0.6214 mile). Thus any ferromagnetic materials at greater depths have lost their magnetic properties.[5, 10]

The intensity of the earth's magnetic field is also interesting to note. If we let B denote the total magnetic intensity of the earth's field at the earth's surface, B_H its horizontal component, and B_V its vertical component, detailed magnetic maps are available giving values for these quantities for all locales on the earth's surface, in addition to other information such as magnetic declination, dip, etc. B varies from a maximum of about 0.7 gauss (1 gauss = 1 line/cm.^{2}) near the south pole to a minimum of about 0.25 gauss off the western coast of South America. B_H has a maximum value of about 0.41 gauss near the equator and a minimum of zero at the magnetic poles. B_V has maximum values similar to B itself, and in the same locations. B_V has minimum values of zero at the magnetic equator, which is quite close to the actual equator.

From the preceding discussion, we obtain the picture that although the earth is non-ferrous in the large, it possesses its own magnetic field that can be approximated by a dipole field, and that the maximum value of this field near the earth's surface is about 0.7 gauss. However, we must now concern ourselves with changes in the earth's magnetic field, because the changes are the cause of problems in power system operation. The changes in the earth's magnetic field can be put into two broad categories: (1) secular variations and (2) transient variations.

Secular variations are slow changes in the earth's magnetic field that take place over tens or hundreds of years. These changes usually continue in the same sense, but not necessarily at a constant rate. Over a long period of time the change can be appreciable, and can result in a reversal of a characteristic, say declination, at a particular point. Needless to say, these secular variations do not cause problems in power-system operation.

The transient variations, so-called because they produce no large and long-enduring changes in the earth's magnetic field, are generally divided into lunar and solar categories. The lunar variations depend on lunar time (hence occur daily), are small in magnitude, and therefore of no importance in our power system considerations. The solar-produced daily variations can be of considerable importance. On the majority of days, the solar variations will be smooth and regular and they are called magnetically quiet or calm days. On other days, the solar variations will be irregular and of greater magnitude; they are magnetically active or disturbed days. When these latter variations are extreme, we have a magnetic storm, which causes problems in power system operation, as evidenced by the many recorded cases. Moreover, these magnetic storms are related to sunspot activity, so that periods of high sunspot activity are almost always followed by magnetic storms on the earth. Let us consider the nature of these magnetic storms.

The Nature of Magnetic Storms

The magnetic storm is a phenomenon that occurs at the earth one or two days after a flare on the visible disc of the sun. A storm of low intensity may cause a magnetic disturbance that is confined to a small part of the earth's surface. An intense magnetic storm causes large magnetic disturbances that commence at almost the same instant of time all over the earth. This statement can be substantiated by comparison of recorded magnetic data from stations in various parts of the world. Most magnetic storms can be characterized by four rather distinct phases: (1) Sudden Commencement, (2) Initial Phase, (3) Main Phase, and (4) Recovery Phase. The component of the earth's magnetic field most affected during a magnetic storm is the horizontal component of field intensity, B_H. Typical averaged changes in B_H during the four phases follow.

(1) *Sudden Commencement* is characterized in low and medium latitudes by an increase in B_H. The averaged increase in B_H is typically 20 to 30 gamma (γ) (1 gamma = 10^{-5} gauss), although it may be as much as 50 to 100 γ. The increase in B_H is largest at equatorial stations and has a rise time of 1 to 6 minutes.

(2) *Initial Phase* follows the sudden commencement and is the period during which B_H is above its normal value. The phase lasts from 2 to 8 hours.

(3) *Main Phase* is the period following the initial phase during which B_H falls below its initial pre-storm value, usually by an amount greater than it exceeded the pre-storm value during the initial phase. An averaged main-phase decrease of 50 to 100 γ is typical, although larger decreases do occur in severe magnetic storms. The main phase of the storm lasts from 12 to 24 hours.

(4) *Recovery Phase* follows the active main phase

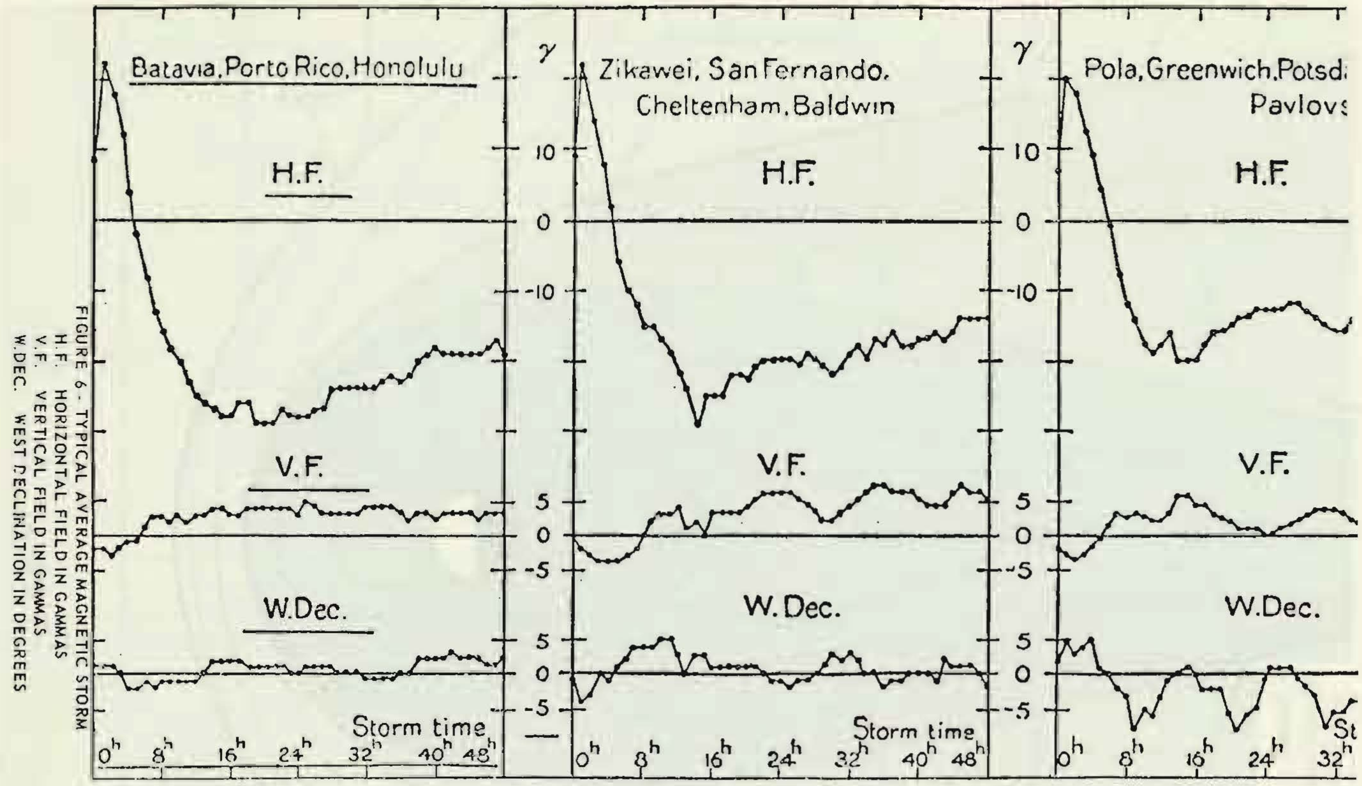

FIGURE 2.

and consists of the slow relaxation of B_{II} back to its initial pre-storm value. The phase may have a time period of from 1 day to 20 or 30 days.

Figure 2 shows averaged magnetic storm data from 11 observatories for a set of 40 storms of moderate intensity, illustrating the phases mentioned above. Figure 2 is taken from Chapman (1951). It must be pointed out that the averaged data does not show the noisy positive and negative excursions of magnetic storms that are probably responsible for power system effects. In Figure 2, the data have been grouped according to approximate magnetic latitude. The magnetic latitude of Batavia, et al., is approximately 22°, that of Zikawei, et al., 40°, and that of Pola, et al., 51°.

Theory of Geomagnetic Field Disturbances

The accepted theory today is that ionization is constantly moving outward from the sun past the earth in a solar wind.[4,7] The solar wind is thought to be made up of two components, a quiet day component resulting from the boiling of the corona, and an active component due to sunspot activity. The solar wind interacts with the ionosphere and the geomagnetic field in ways that are not yet fully understood. A proposed quiet-day model, taken from Levine (1966), is shown in Fig. 3.

During periods of sunspot activity the flow of electrified particles toward the earth is increased. As these particles come under the influence of the earth's magnetic field, it is believed that those with certain energy levels will reach the atmosphere with greatest densities in belts near the magnetic poles (auroral zones) at altitudes of the order of 100 to 300 kilometers (60 to 180 miles) or more.[2, 9] The charged particles that are concentrated in the auroral zones cause very large currents to circulate in the atmosphere, of the order of 1,000,000 amperes. During a magnetic storm, these auroral-zone currents can change rapidly, giving rise to rapidly-changing magnetic field disturbances in northern latitudes. It is believed that such auroral storms cause the greatest disturbances on power systems and, of course, also give us the visual aurora borealis displays.

In addition to the concentration of charged particles in the auroral zone, it is believed that particles of some other energy level are concentrated in the plane of the magnetic equator, forming a "ring current" around the earth. This ring current is thought to be in the magnetosphere, and hence at much higher altitudes than the auroral currents, and that it is associated with the Main Phase of the magnetic storm. The authors of this paper do not feel that power system effects are caused by Main Phase phenomena.

Earth Potentials During Magnetic Storms

During magnetic storms, surface earth potentials of the order of 5 to 10 volts per mile have been recorded.[8] These earth potentials generally occur in the northern latitudes and are believed to be due to the auroral magnetic storms (auroral currents). The earth potentials are, of course, accompanied by earth currents.

The calculation of the storm-induced earth potential and its associated current is rather complex and requires knowledge of the time variation in the magnetic-field

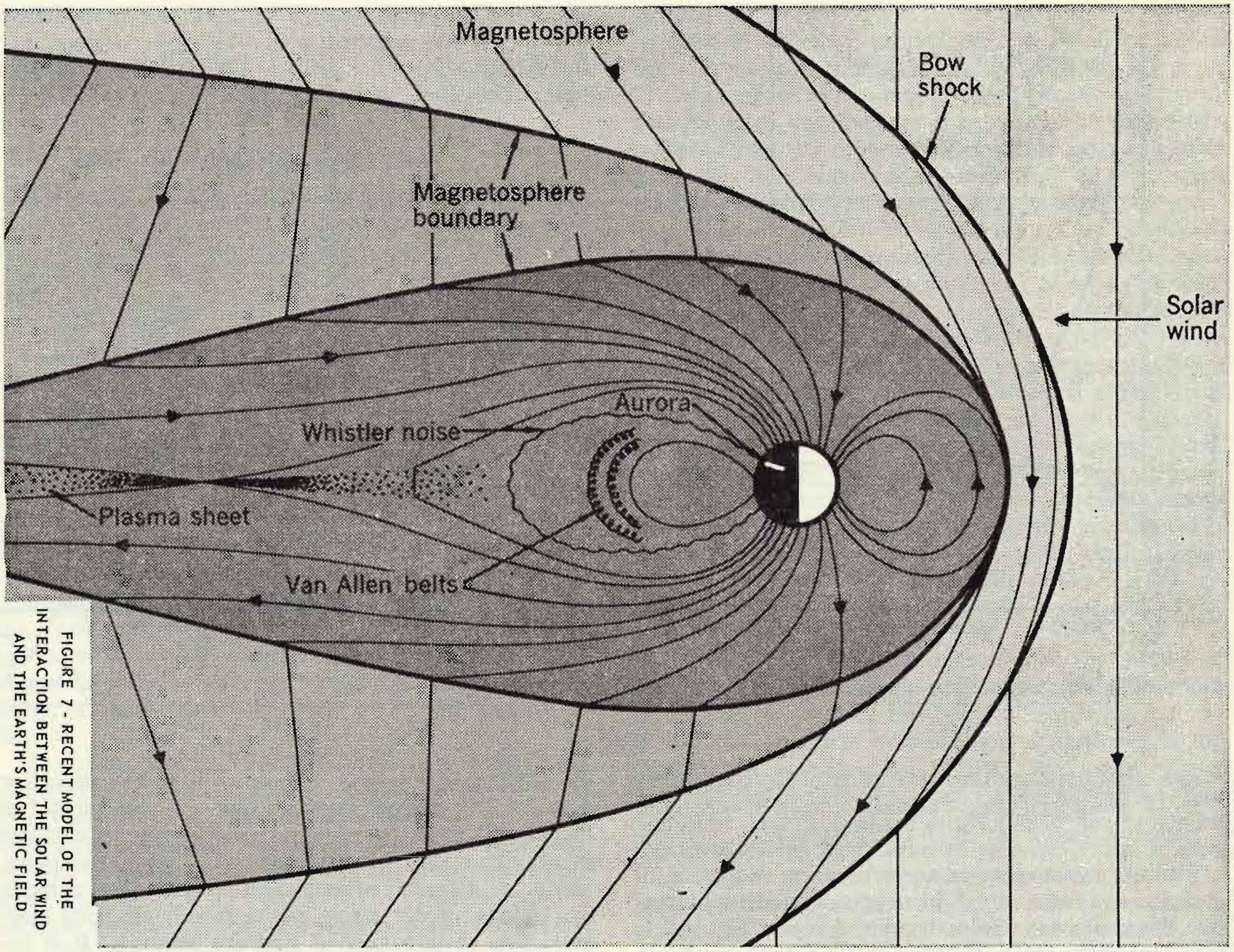

FIGURE 3.

disturbance, the conductivity of the earth as a function of depth, and the permeability of the earth as a function of depth (all available information indicates relative permeability to be approximately unity).

McNish (1940) used equation (1) to calculate the earth potentials due to auroral currents.

$$E = \frac{dA}{dt} = \frac{d}{dt}\left[\int \frac{I\,ds}{r}\right] \qquad (1)$$

E = induced earth potential.

A = magnetic vector-potential.

I = current flowing in the atmosphere (auroral current).

r = distance from auroral current to point at which A is being calculated.

ds = element of length along the path of the auroral current.

Using equation (1), and assuming (a) a path of auroral current 2500 Km in length of infinitesimal cross-section, (b) an altitude of 200 Km for the auroral current, and (c) changes in the intensity of the auroral currents of from 10,000 to 15,000 amperes per second, McNish calculated the earth potentials shown in Figure 4.

Kellog[6] of the University of Minnesota Physics Department assumed a magnetic field disturbance wave (due to changes in the auroral currents) oscillating with time and propagating vertically into the ground. This wave will be attenuated with depth into the ground and its fundamental-frequency fourier-series component is represented by

$$B(t,z) = B_g \epsilon^{j(\omega t - k_g z)} \qquad (2)$$

B_g = magnitude of the magnetic field disturbance wave at the surface of the earth in gauss.

j = complex operator.

ω = radian frequency of the fundamental component of the fourier series representation of the disturbance wave.

t = time in seconds.

k_g = attenuation factor for depth into ground in centimenters.

z = depth into ground in centimeters.

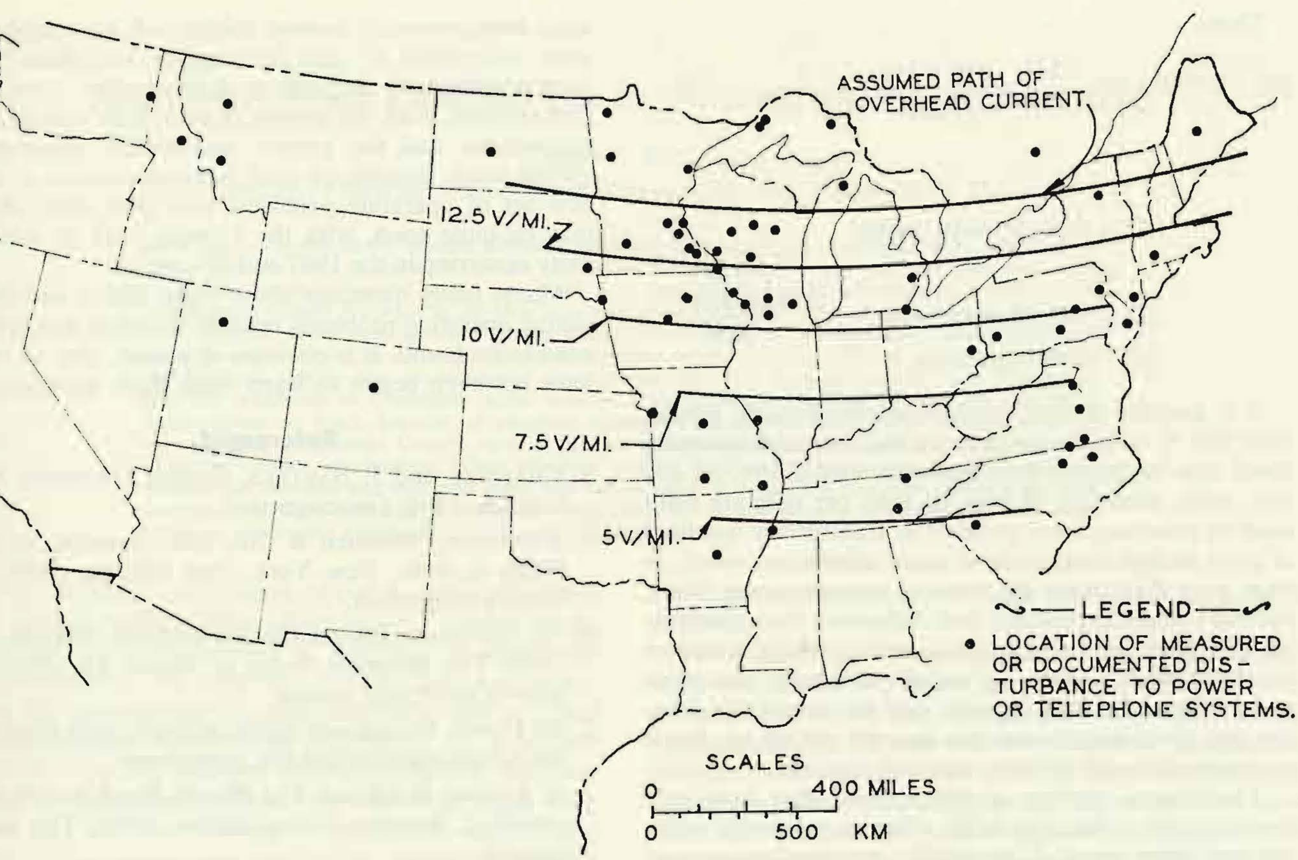

FIGURE 9 · EARTH POTENTIALS AS CALCULATED BY McNISH

FIGURE 4.

The solution to equation (2), which depends on fitting boundary conditions at the earth's surface, and the application of one of Maxwell's equations, gives the following results:

(a) A horizontal electric field exists at the earth's surface given by

$$|E| = 2.998 \times 10^{4} \left| \frac{\omega}{k_g C} \right| Bg \qquad (3)$$

where C = velocity of light in centimeters/sec.
E = volts/meter.

(b) skin depth in kilometers is given by

$$d = 0.5 \sqrt{\frac{T}{\sigma}} \qquad (4)$$

where d = skin depth in kilometers in the conducting earth.
T = period of the wave in seconds.
σ = conductivity of the earth in mho/meter.

(c) the nature of kg is:

$$\frac{1}{k_g} = \frac{d}{\sqrt{2}} = \sqrt{\frac{C^2}{4\Pi\sigma\omega}} \qquad (5)$$

Equations (4) and (5) indicate that skin depth, d, and hence k_g, can be calculated if conductivity, σ, is known (along with T or ω). However, σ is not uniform with penetration into the earth. There is, therefore, difficulty in using (4) and (5) directly, and thus our knowledge of the earths' composition must be used in conjunction with (4) and (5). The surface layer of the earth, perhaps to a depth of 20 to 40 miles, has relatively good conductivity similar to that of moist sand or loam.[5,1] Below this higher conductivity layer, the earth seems to be composed of a much higher resistivity, semiconductor type of material,[6] whose resistance varies with temperature. At depths of a few hundred miles, the temperature rises to, say, 2000 degrees, and the conductivity begins to increase very rapidly. The result is that waves of period 1 minute or longer (corresponding to that of the magnetic disturbance waves) have an effective skin depth of the order of 600 km (400 miles).

To get an estimate of E from equation (3), a change of 250 V, with a period of 6 minutes, is quite reasonable [12] during a magnetic storm.

The values, then, are as follows:

$$k_g = \frac{\sqrt{2}}{600 \times 10^5}$$

$$\omega = \frac{2\Pi}{360}$$

$$c = 3 \times 10^{10} \text{ cm/sec.}$$

$$Bg = 250 \times 10^{-5} \text{ gauss}$$

Then:

$$|E| = 2.998 \times 10^4 \left[\frac{2\Pi}{360} \cdot \frac{600 \times 10^5}{\sqrt{2}} \cdot \frac{1}{3 \times 10^{10}} \cdot 250 \times 10^{-5} \right]$$

$$|E| = 0.00185 \text{ volts/meter}$$

or

$$|E| = .00185 \text{ volts/meter} \times \frac{1609 \text{ meters}}{\text{mile}}$$

$$|E| = 2.98 \text{ volts/mile}$$

It is possible to have excursions considerably greater than 250 V with similar periods and the earth potential could thus be greater than that calculated above. At any rate, earth potentials of 5 to 10 volts per mile are sufficient to produce direct currents in transformer windings of great enough magnitude to cause saturation, which, in turn, may then cause the unusual reactive power flows, the bus voltage excusions,[3] and difficulties from harmonics that have been documented and to which reference has been made. Again, as stated previously, the exact paths followed by the currents and the magnitudes during any given disturbance can be only estimated, but it is evident that such currents can and do exist.

There are a number of other effects that have only been inferred so far. One is the effect on pilot-wire relaying and other physical or metallic communications systems resulting from shifts in earth or ground potentials. And neither space radio nor microwave circuits provide a ready solution to this problem inasmuch as they are at least as susceptible — if not possibly more so — to interruptions from magnetic storm activity as physical wire circuits themselves. A microwave receiver, for instance, might suddenly find itself receiving interfering signals from another microwave system hundreds of miles away, due to greatly enhanced radio propogation characteristics. Even power line carrier circuits should theoretically be susceptible to interruptions or interference from higher-frequency pulsations in the geomagnetic field.

Conclusions

It is apparent that the effects on power systems from solar-magnetic disturbances are not at all well documented and even less well understood. It is also apparent, however, that these solar and geomagnetic phenomena can cause large and potentially serious disturbances on electric-power systems and their associated relaying, telemetering, supervisory control and communication systems.

And it would appear from the foregoing analysis that large interconnected systems might well be considerably more susceptible to such interruption and disturbances from geomagnetic fluctuations than smaller, more compact systems. Wtih the growth of extra-high voltage interconnections and the greater and greater geographical spread made possible by such interconnections, a whole new set of operating problems may well arise. And it may be quite soon, with the 11-year peak in solar activity occurring in the 1967 to 1971 period.

Many, many questions about these effects and the resulting operating problems need to be asked and answers need to be found. It is obvious, of course, that so far we have not even begun to learn what these questions are!

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