Occurrence Frequency of Geomagnetically Induced Currents: A Case Study on a B.C. Hydro 500 kV Power Line

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Two empirical formulas were derived which jointly make it possible to predict size of GIC (geomagnetically induced current) in a power line as a function of Kp , a three-hourly planetary magnetic activity index. GIC size is represented by an hourly-range value, i.e., the difference between the maximum and minimum GIC values for a time interval of an hour. The formulas are based on the data obtained from a 500 kV power line of B.C. Hydro which extends 400 km long in an east-west direction at a geomagnetic latitude of about 60° . One of the two formulas relates mean GIC size with Kp ; it was found that, on the average, GIC size changes exponentially with Kp . The other formula describes the scatter of individual values of GIC size about the average trend described by the first formula. The scatter was found to follow a lognormal distribution. The parameters in these formulas were determined from two groups of data: one includes the entire available data and the other covers data for $1+ \leq Kp \leq 5_0$. The data outside this Kp range were scanty. The probability that GIC size exceeds 100 Amperes at $Kp=9$ is estimated to be 3% and 12%, respectively, based on the two data groups.

1. Introduction

A systematic investigation of the influence of magnetic storms on power transmission systems was initiated in the late 1960's by V. D. ALBERTSON *et al.* (1973, 1974a, 1974b, 1979). They noted a number of adverse effects caused by magnetic storms. Some of these effects, i.e., generation of excessive harmonics, misoperation of protective relays and system voltage fluctuations were also experienced by B.C. Hydro during the past several years (WATANABE and SHIER,

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1982). However, little quantitative information is available on how often and to what degree a magnetic disturbance affects power transmission systems. The aim of our research reported herewith was to obtain this information.

According to ALBERTSON *et al.* (1973, 1974a, 1974b, 1979), almost all magnetic storm effects on power transmission systems are attributed to solar induced currents (SIC) which are now referred to as geomagnetically induced currents (GIC). Magnetic disturbances give rise to earth surface potential gradients (ESPG) which in turn cause GIC's in a power transmission line grounded at two locations or more. If so, to find a relationship between the size of GIC and the degree of magnetic disturbance is a logical step to take in our investigation. In this particular research, the GIC size is represented by its hourly-range value, i.e., the difference between the maximum and minimum values for a time interval of an hour. In a power system, effects caused by GIC are related to GIC magnitude, i.e., the zero-to-peak value. In general, GIC magnitude is found to be about half the hourly-range value since positive- and negative-going excursions of GIC are about equal in magnitude. The degree of magnetic disturbance is represented by the *Kp* index, a three-hourly planetary magnetic index (refer to MAYAUD (1980) for details). The GIC data were obtained in August 1979 at the B.C. Hydro Williston Substation near Prince George, B.C. (Fig. 1). This is at the eastern end of a 400 km power line, running in an east-west direction at a geomagnetic latitude of about 60°. This power line is part of the 500 kV power system in B.C. However, it is isolated DC-wise from the other 500 kV power lines because of the four series capacitors placed in the system. At Williston Substation the power line is grounded through three Y-connected 3 phase power transformers, T1, T2 and T4, and five 3 phase reactors. The transformers and reactors are parallel to one another. The transformer T4 is least resistive. Just about one third (34%) of GIC flows through the neutral connection of T4. The GIC data were measured in this neutral connection. The frequency response of the whole GIC detection/recording system is flat from DC to 2 Hz (BOTELER, 1979). Reference is made to D. H. BOTELER *et al.* (1982) for more details of GIC measurements.

In the analysis of data we calculate the mean relationship between GIC size and *Kp*; we also assess the nature of the statistical variation of GIC about the mean level. These factors are then combined to determine the possibilities of GIC size exceeding specified values for different values of *Kp*. Factors affecting the relationship between GIC size and *Kp* and the statistical variations of GIC size are also discussed.

2. Analysis of Data

The GIC recording was done continuously from 00h UT on Aug. 4 to 13h UT on Aug. 30 (636 hrs) in 1979. The observation was successful except for four time intervals. In total, 38 hours of data were lost resulting in 598 hours of usable data. For each hour interval, the maximum and minimum values were

Fig. 1. B.C. Hydro 500 kV System. Four series capacitors are installed in the line from the Gordon M. Shrum Generating Station to the Ingledow Substation and are shown by the four bars perpendicular to the power lines. The map covers an area in geographic coordinates, 48°N to 57°N and 117°W to 132°W.

measured (Fig. 2) and their difference (hourly-range value—GIC size) was calculated.

During the 598 hours of successful observation, the Kp values fell in a range $1+ \leq Kp \leq 5_0$ more than 80% of the time. Kp was greater than 5_0 in only 7% of the total time interval. The sample distribution with Kp is indicated in Fig. 3. Kp has a range of 0 to 9 with each level subdivided into three: e.g., 3_- , 3_0 , 3_+ . MAYAUD (1980) introduced a new scale in which each division is replaced by a number in the range of 0 to 27 which he called $3 Kp$ but is here noted

Fig. 2. GIC observed at Williston Substation, Prince George, B.C. in August, 1979. GIC flowing from the transformer to ground is taken positive. The upper and lower curves represent the hourly maximum and minimum values, respectively. The data were lost due to malfunction of the amplifier during the four time intervals: 16d 23h-17d 23h (24 hrs), 23d 04h-23d 06h (2 hrs), 23d 15h-24d 01h (11 hrs) and 29d 07h-29d 08h (1 hr).

Fig. 3. GIC sample distribution with Kp . Out of 598 hour intervals of successful observation, 82% fall in a range, $1+ \leq Kp \leq 5_0$. Hour intervals with $Kp > 5_0$ occupy 7% of them all.

with a new symbol, u , for convenience. The dependence of GIC size on Kp is shown in Fig. 4. The common log of GIC is plotted on the ordinate. One small division on the abscissa corresponds to one unit of the u index. Two regression lines are also shown in this figure. The line which is less steep, is based on the entire data whereas the other concerns the data for $1+ \leq Kp \leq 5_0$. The regression lines imply that GIC size varies exponentially with Kp . The relation may be expressed as

$$I_m = I_0 e^{\beta u} \quad (1)$$

where I_m is mean GIC size, and I_0 and β are parameters which were computed for the two data groups. The results are presented in Table 1. With these constants Equation (1) shows that I_m increases by a factor of 1.73 (the less steep

Fig. 4. Distribution of GIC size with Kp . The two regression lines correspond to two groups of GIC data; one, the steeper line, to the data for $1+ \leq Kp \leq 5.0$, and the other, the less steep, to the entire data.

Table 1. Constants for Eq. (1), $I_m = I_0 e^{\beta u}$, obtained from the regression analysis of the two data groups.

Data Group	I_0 (Ampere)	β
$0 \leq Kp \leq 9$	0.180	0.182
$1+ \leq Kp \leq 5.0$	0.148	0.209

regression line) or 1.87 (the steeper one) as Kp increases by 1 (u by 3). Figures 5(a) and 5(b) show how individual GIC size values are scattered about the regression line. The abscissa represents the ratio of a GIC size I to that of the mean GIC size I_m given by Eq. (1). More explicitly, the abscissa represents x defined by

$$x = I/I_m = (I/I_0)e^{-\beta u}. \quad (2)$$

The Kp dependence of I is removed in x . This can be regarded as the GIC size reduced to a magnetic disturbance level $Kp=0$, putting the proportionality cons-

Fig. 5. Histogram of GIC size reduced to $K_p=0$. It indicates scatter in GIC distribution about the average trend shown by the regression lines in Fig. 4 or Eq. (1). Figure 5(a) corresponds to the entire data and Figure 5(b) to the data group $1+ \leq K_p \leq 50$. The smooth solid curve in each figure is the lognormal distribution fitted to the histogram.

tant I_0 aside. Figures 5(a) and 5(b) show the distribution of x , referred to as normalized GIC. Figure 5(a) deals with the data group covering the entire Kp range whereas Figure 5(b) concerns the data for $1+ \leq Kp \leq 5_0$. Each of the histograms, Figures 5(a) and (b), indicates that with the Kp dependence removed the GIC size values follow a lognormal distribution. The probability density function $P(x)$ of a lognormal distribution is given by

$$P(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp \left[-\frac{(\ln x - m)^2}{2\sigma^2} \right] \quad (3)$$

where the parameters σ and m are related to the mean value M of x and the variance S , as follows (KAWADA and MARUYAMA, 1966),

$$M = \exp \left(\frac{\sigma^2}{2} + m \right) \quad (4)$$

and

$$S = e^{\sigma^2 + 2m}(e^{\sigma^2} - 1). \quad (5)$$

For the two data groups, the mean and variance of the variable x were computed from which σ and m were determined using Eqs. (4) and (5). The results are presented in Table 2.

Table 2. Parameters in the probability density function of a lognormal distribution (Eq. (3)), calculated for the two data groups.

Data Group	σ^2	m
$0 \leq Kp \leq 9$	0.598	-0.0322
$1+ \leq Kp \leq 5_0$	0.562	-0.0241

The probability density function $P(x)$ given by Eq. (3), together with the computed values of σ and m , make it possible to estimate the probability that for a given value of u (or Kp) the GIC size becomes equal to or greater than a specified value I_c . A few steps of calculation yields the following expression for the probability,

$$\text{Prob. } (I \geq I_c; u) = 1 - F \left(\frac{\ln x_c - m}{\sigma} \right) \quad (6)$$

where

$$x_c = I_c / I_m(u) \quad (7)$$

and $F(y)$ is the normal distribution function,

$$F(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^y e^{-\frac{t^2}{2}} dt. \quad (8)$$

The probability was computed for twelve different values of I_c from 1 A to 200 A for each level of u (or Kp). The results are presented in Figs. 6(a) and 6(b) and in Tables 3(a) and 3(b). Figure 6(a) and Table 3(a) concerns the data group of the entire Kp range and Figure 6(b) and Table 3(b) the data for $1+ \leq Kp \leq 5_0$. The probability that the GIC size be equal to or greater than 100 A for $Kp=9$ is about 3% based on the data of the entire Kp range and is about 12% for the other group of data.

There are two alternative explanations for the different results for the two data groups. One is that the law expressed by Eq. (1) does not hold for the entire Kp range. The other is that it does hold for the whole Kp range but that the data were meagre, especially for the lower and higher Kp ranges, which gave rise to the uncertainties in the parameters, I_0 and β . If the first is the case, the discrepancies will not be resolved no matter how much data may become available. If the second is the case, however, the discrepancies will be reduced with more data. To determine which is the case, warrants more investigation.

3. Comparison with Observation at High Latitudes

Comparison with GIC at other locations is not straightforward because of generally different configurations. However, ESPG values may be relevant at other locations.

Equation (1) can be converted to a formula relating the hourly-range value of ESPG (mean) to Kp . The power line which we dealt with has four substations and at each of these, the power line is grounded, so far as GIC is concerned, via 3-phase Y-connected power transformers with grounded neutrals. The grounding resistance at every substation, i.e., the parallel resistance of the 3-phase power transformers plus the station ground resistance, is one order of magnitude smaller than the line resistance between the adjacent stations. Therefore, the earth surface potential difference between Williston and its adjacent substation, Glenan-nan, divided by the line resistance between the two is almost equal to the strength of the GIC at Williston. Let V , R and I be the potential difference (an instantaneous value), line resistance of all three phases in parallel and GIC (an instantaneous value) at Williston through the neutral connection of T4, the 3 phase transformer. Note that I is one third (34%) of the GIC at Williston. Thus,

$$V/R = I/0.34. \quad (9)$$

The line resistance is 4.33Ω per phase. Hence, $R = 1.44\Omega$. From the above equation and Eq. (1), the mean hourly-range value of the potential difference, V_m ,

Fig. 6. Probability for GIC size to be equal to or greater than a specified value. The Kp value, changing from 0 to 9 stepwise, is indicated as a parameter. Figure 6(a) corresponds to the entire data and Figure 6(b) to the data group $1+ \leq Kp \leq 50$.

is related to u as

$$V_m = V_0 e^{\beta u} \quad (10)$$

where

$$V_0 = \frac{RI_0}{0.34} = \begin{cases} 0.76 \text{ Volt} & (0 \leq K_p \leq 9), \\ 0.63 \text{ Volt} & (1_+ \leq K_p \leq 5_0). \end{cases} \quad (11)$$

The mean hourly-range value of ESPG, E_m is obtained by dividing V_m with the separation distance, L , between Williston and Glenannan. Since $L = 174$ km, we have

$$E_m = E_0 e^{\beta u} \quad (12)$$

where

$$E_0 = V_0/L = \begin{cases} 4.4 \times 10^{-3} \text{ Volt/km} & (0 \leq K_p \leq 9), \\ 3.6 \times 10^{-3} \text{ Volt/km} & (1_+ \leq K_p \leq 5_0). \end{cases} \quad (13)$$

For $u = 27$ ($K_p = 9$), V_m and E_m turn out to be 104 volts and 0.60 volt/km for the data group, $0 \leq K_p \leq 9$, and 177 volts and 1.0 volt/km for the other data group. It should be noted that E_m implies surface electric field averaged over the distance, L . It does not represent local electric field unless the field is uniform in space.

Our results are based on a power line at a geomagnetic latitude of approximately 60° . However, we surmise that the exponential relation between E_m and u ($3K_p$) holds at other latitudes with the same value for the coefficient β since K_p is a planetary index. But the proportionality constant, E_0 , should be different for different latitudes. Even at comparable latitudes, it may not be the same because of possible differences in the local electrical conductivity of the earth.

W. H. CAMPBELL (1980) investigated GIC's in the Alaska oil pipe line which runs north-south from Prudhoe Bay on the Arctic Ocean to Valdez on the Gulf of Alaska. The strength of the pipe line current (an instantaneous peak value) at Fox Junction, a midpoint of the pipe line, was found to be related to the Ap index as follows, putting statistical scatter aside (Ref. to Eq. (20) of CAMPBELL (1980)),

$$I = 5.02 Ap - 0.753. \quad (14)$$

The current strength is measured in Amperes. This relation can be rewritten into a formula connecting ESPG, E_m , to u , providing that the pipe line's resistance and the K_p/Ap relation are known. The pipe line's resistance is $4.82 \times 10^{-6} \Omega/\text{m}$. The K_p index is a semi-logarithmic scale of Ap (Ref. to Table 6, p. 47 of MAYAUD (1980) or Fig. 7 of CAMPBELL (1980)): the relationship is not quite logarithmic but very closely so. A linear regression analysis of $\ln Ap$ vs u for

Table 3(a). Probability of GIC occurrence.

Index		GIC Size											
Kp	U	1	2	3	5	7	10	20	30	50	70	100	200
0	0	0.013	0.001	0.000	0.000	0.000	0.000	—0	—0	—0	—0	—0	—0
	1	0.024	0.002	0.000	0.000	0.000	0.000	—0	—0	—0	—0	—0	—0
1	2	0.040	0.004	0.001	0.000	0.000	0.000	—0	—0	—0	—0	—0	—0
	3	0.065	0.008	0.002	0.000	0.000	0.000	0.000	—0	—0	—0	—0	—0
	4	0.101	0.015	0.004	0.000	0.000	0.000	0.000	—0	—0	—0	—0	—0
2	5	0.149	0.026	0.007	0.001	0.000	0.000	0.000	—0	—0	—0	—0	—0
	6	0.211	0.045	0.013	0.002	0.000	0.000	0.000	0.000	—0	—0	—0	—0
	7	0.285	0.072	0.023	0.004	0.001	0.000	0.000	0.000	—0	—0	—0	—0
3	8	0.370	0.110	0.040	0.008	0.002	0.000	0.000	0.000	0.000	—0	—0	—0
	9	0.462	0.161	0.065	0.015	0.005	0.001	0.000	0.000	0.000	—0	—0	—0
	10	0.556	0.225	0.100	0.026	0.009	0.002	0.000	0.000	0.000	0.000	—0	—0
4	11	0.646	0.301	0.148	0.044	0.016	0.005	0.000	0.000	0.000	0.000	—0	—0
	12	0.729	0.388	0.209	0.071	0.028	0.009	0.001	0.000	0.000	0.000	0.000	—0
	13	0.801	0.480	0.283	0.109	0.048	0.017	0.001	0.000	0.000	0.000	0.000	—0

[illegible]

N. B. Based on the data $0 \leq Kp \leq 9$.

$0_+ \leq Kp \leq 9$ ($1 \leq u \leq 27$) shows that the correlation coefficient is more than 0.997 and that the slope of the regression line— $\ln Ap$ (ordinate) and u (abscissa)—is 0.192 with the intercept on the ordinate 0.8587. With these results, Equation (14) is rewritten as follows,

$$E_m = 5.71 \times 10^{-2} e^{0.192u} - 3.63 \times 10^{-3} \quad (15)$$

where E_m is in units of volt/km. If we limit ourselves to a range of Kp , $1_+ \leq Kp \leq 5_0$, a linear regression analysis yields an even higher correlation coefficient, leading us to the following expression,

$$E_m = 5.19 \times 10^{-2} e^{0.209u} - 3.63 \times 10^{-3}. \quad (16)$$

Equations (15) and (16), which are based on Eq. (14) (Campbell's result), are similar in mathematical form to our result, i.e., Eq. (12). The constant term (the second term) on the right hand side of Eqs. (15) and (16) has no counterpart in Eq. (12), however. The reason for this discrepancy may be that we dealt with hourly-range values whereas Campbell dealt with instantaneous peak values. Practically, the discrepancy is unimportant anyway. The constant term in Eq. (15) or Eq. (16) is negligible: it is one order of magnitude smaller than the first term, the exponential function, even for $u=0$. The coefficient to the power index in Eq. (15), i.e., 0.192, is quite close to our value of 0.182 for the case of the data group $0 \leq Kp \leq 9$ (see Table 1). The coefficient in Eq. (16), i.e., 0.209 is just equal to our result for the case of the data group $1_+ \leq Kp \leq 5_0$. The proportionality constant in Campbell's case, i.e., $5-6 \times 10^{-2}$ volt/km, is greater than ours by a factor of about 15. The difference is presumably about double if Campbell's result which concerns instantaneous peak values is converted to hourly-range values. It could be even larger if we recall that the pipe line used by Campbell runs in a north-south direction. ESPG in an east-west direction seems to be greater statistically than that in a north-south direction. Generally, GIC is expected to be greater in Alaska than in B.C. However, it requires more investigation to see if the contrast between the Alaska pipe line result and ours is attributable to latitude difference only.

4. Discussion

The investigations reported herewith can be improved in several ways. First of all, GIC size (hourly-range value) should be compared with hourly magnetic indices, e.g., AE (auroral electrojet activity index—refer to MAYAUD (1980) for details). Comparison with hourly-range values of the magnetic field variation at a nearby location should also be made. This will be particularly sensible if a permanent magnetic observatory exists in a general area of the power line of interest. In the case of our power line, the data from the Victoria Magnetic Observatory, Victoria, B.C. and also from the Meanook Magnetic Observatory

near Edmonton, Alta, will be usable. Both are permanent observatories under the auspices of the Earth Physics Branch, Dept. of Energy, Mines and Resources, Government of Canada.

The GIC records that we acquired indicate that the GIC frequency spectrum, on the average, has a broad peak covering a range of periods from 5 min to 3 hrs. Fluctuations on a time scale of 1 hr. are most common, and this is why we used hourly-range values to represent GIC activity. However, it should be noted that the largest GIC observation which we experienced was a much more rapid fluctuation. It occurred on Aug. 29, 1979. The peak-peak change was about 40 Amperes. Its waveform was a single oscillation—up, down and back to an average level—with a time scale of about 10 minutes. The Kp value was only 6₀. We feel that spiky variations of this type deserve special attention. Another example is a GIC event on April 13, 1981. A relay misoperation caused a 500 kV line to trip out at 07:09 UT on that day at Glenannan Substation (WATANABE and SHIER, 1982; BOTELER *et al.*, 1982). No GIC observation by us was in progress at that time but the Victoria Magnetic Observatory recorded one large oscillation of about 10 min duration. The variation was particularly clear in the vertical component. The peak-peak change was about 1,000 nT.

As well as the need for the frequency spectrum of GIC to be investigated further, the distribution of GIC in space (wave number spectrum) should also be investigated as very little is known about this matter. The distribution in space is particularly interesting to investigate if short time-scale spiky variations mentioned in the previous paragraph are really adverse for power transmission systems. Short-time scale variations may be relatively localized compared with long time-scale variations. The power line dealt with in this paper suits an investigation of this problem. The four substations on this line are spaced at almost equal distances (Fig. 1) so that simultaneous observations at all four stations are likely to enable us to resolve variations in space with a resolution of ~ 200 km.

5. Conclusions

The main results obtained are as follows:

(i) Mean GIC size increases exponentially with Kp . Refer to Fig. 4 and Eq. (1). The coefficients in Eq. (1) were found for the two different data groups and are listed in Table 1.

(ii) The scatter of individual GIC size data about the average trend expressed by Eq. (1) were found to follow a lognormal distribution. Refer to Figs. 5(a) and 5(b), Eq. (3) and Table 2.

(iii) The two empirical formulas, Eqs. (1) and (3), make it possible to estimate the probability that the GIC size, for a given Kp value, exceeds a specified limit. Refer to Eq. (6) and Figs. 6(a) and 6(b) and Tables 3(a) and 3(b).

(iv) Equation (1), GIC size vs Kp relation, can be reduced to a ESPG size vs Kp relation, i.e., Eq. (12). This relation is virtually identical in form to the ESPG vs Kp relation inferred from the GIC observation made on the Alaska

oil pipe line. The coefficient β obtained from the Alaska oil pipe line data is almost equal to our result. However, E_0 , the proportionality constant in Eq. (12) is estimated to be greater in Alaska by about one order of magnitude and possibly more.

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