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Effects of solar activity in the Czech Republic

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Abstract

Due to the interaction of solar wind with magnetosphere eruptive events on the Sun have an impact on the immediate surroundings of the Earth. Through induction of electric currents, they also affect Earth-bound structures such as the electric power transmission networks. We investigate the effect of the geomagnetic activity represented by the K-index on the Czech electric-power grid represented as disturbances recorded in 12 years in the maintenance logs. We find that in case of the data sets recording the disturbances on power lines at the high and very high voltage levels and disturbances on electrical substations, there is a statistically significant increase of anomaly rates in the periods of tens of days around maxima of geomagnetic activity compared to the adjacent minima of activity. Moreover, we computed GICs for two (east–west and north–south oriented) high voltage transmission lines in the Czech Republic and found surprisingly high values of currents in the order of tens of amperes. In hand, with satellites data, we studied propagation and properties of the largest CMEs with respect to their relation to the disturbances in the transmission networks of the Central European countries. Our results provide a piece of evidence that the geomagnetically induced currents may affect the occurrence rate of anomalies registered on power-grid equipment even in the mid-latitude country in the middle of Europe.

1 Introduction

Despite the known effect of increased solar activity on space technology or the Earth itself, only a few researches related to this issue has been done so far. Most of the available work deals with the immediate effects registered on the infrastructure during or shortly after significant disturbances in solar activity. Most of them describe Hydro-Quebec blackout in 1898 caused by 13 and 14 March superstorm [1]. Recently, research has been focused on a long-term impact of fluctuating solar activity on the network infrastructures, even in cases of less important events than Quebec blackout [2, e.g]. For example, there is a study by [3] focused on the Greek electric grid and the disturbances on its key components.

One of the aims of this work was to make comparable analyzes for disturbances recorded in a Czech distribution network and determine the relationship between the failures of the grid components and increased geomagnetic activity in the Czech Republic. This relationship may tell us more about the statistical significance of the failure rates within geomagnetic active days. In this study, we present the first detailed statistical analysis of the effects of solar activity in the Czech Republic. In this manner, we modelled the geoelectric field using one-minute geomagnetic measurements from Intermagnet database. We applied this model to the long-term measurements of the geomagnetic field during the period of increased solar activity (for example in days when the aurora was observed) and considered possible destructive effects on the distribution network infrastructures. Moreover, using the geoelectric field we computed GICs for two (east–west and north–south oriented) high voltage transmission lines in the Czech Republic and found surprisingly high values of currents in the order of tens of amperes.

The prediction of the occurrence of solar flares and CME is crucial as even small changes in solar activity can adversely affect the Earth 's conductive systems and telecommunications. Because of that, a probabilistic assessment of the likelihood of such events and their strengths is necessary. To be able to forecast space weather we first need to understand physics behind it from coronal heating problem to interactions of the supersonic solar wind with Earth 's magnetosphere and following effects on near Earth-space environment. In this study, we present the first detailed statistical analysis of the effects of solar activity in the Czech Republic.

2 Background

The solar wind and IMF carried by it connect the solar atmosphere with the Earth but the Earth itself is not affected by solar wind directly since its impact is largely shielded by the Earth's magnetic field. The large-scale propagating structures in interplanetary space that originate from the solar wind streams and transient solar eruptions cause disturbances in the geomagnetic field [4] that represent a potential risk to influence the performance and reliability of both space-borne and ground-based technological systems and even endanger human life or health through radiation exposure. The solar-activity disturbances induce disturbances in the magnetosphere, called the geomagnetic activity. Significant fluctuations of the geomagnetic activity are called geomagnetic storms. The level of geomagnetic activity can be most easily expressed by measuring the Earth's magnetic field strength of the surface. From the measured geomagnetic field and its evolution in time a variety of indices of geomagnetic activity are constructed.

CMEs and their subset, magnetic clouds (MCs), are twisted magnetic flux tubes carrying a significant amount of magnetic flux and helicity, mass and energy outward from the Sun to the interplanetary medium [5]. They are responsible for major geomagnetic storms [6] because they are usually associated with interplanetary shocks and large southward interplanetary magnetic field which is essential for magnetic field reconnection.

Furthermore, interplanetary pressure events like interplanetary shocks, connected with both CMEs or corotating interaction regions (interaction region of fast solar wind stream with the ambient slower solar wind due to the rotation of the Sun) compress or expand Earth's magnetosphere and increase or decrease the magnetopause and tail currents result in changes of other near-Earth current system. The interaction of the supersonic solar wind with the Earth's dipole magnetic field is surprisingly complicated because spatial scales differing by 5 orders of magnitude and timescales from seconds for the auroral pulsations [7], to several minutes for the reaction of the global magnetosphere to solar-wind pressure changes [8], to several days for the intensification of the electron radiation belt [9] are involved in the global behavior of the magnetospheric system.

What we know so far is that shock wave causes changes in the system of currents of the magnetosphere and ionosphere that generates a time-varying electric field see [10]. This geoelectric field, in turn, gives rise to geomagnetically induced currents (GICs) in the conductive structures on the Earth's surface. The GICs arise due to voltage differences between the endings of grounded conductor and can produce damage in the system attached to the conductor such as railways [11], pipelines [12] and particularly in power networks [13]. The presence of GICs in the electric power transmission network may interfere with their normal operation and cause damage resulting in a failure or service disruption that happened a several times in past ass well e.g, Quebec blackout from 1989. GICs consist possible trouble for network transformers [14].

3 Methods & Results

We worked with the lists of disturbances recorded in the maintenance logs by the company technicians with their dates and many more details, which included also the probable cause of the failure. The lists contained not only the events of the equipment failure (e.g. defects), but also the events on the power lines, such as the repeated unplanned switching, power cuts, or service anomalies. The inhomogeneous data sets were split into 12 subsets D1–D12, which were investigated separately. Each sub-data set was selected so that it contained only events occurring on devices of a similar type and/or with the same voltage level and were recorded by the same operating company.

To assess the effects of solar/geomagnetic activity to power grids, we used the measurements of the geomagnetic field from the nearest measuring station, the Geomagnetic Observatory Budkov in Šumava mountains, operated by the Geophysical Institute of the Czech Academy of Science. They produce minute measurements of the full vector of the induction of the geomagnetic field. From these measurements, we constructed a K index, which is typical for characterizing the level of geomagnetic activity in similar applications.

Using a different method of statistical analysis we provided a comprehensive study of the relationship between the level of geomagnetic activity and failure rates in the spine of the Czech power-distribution grid. We compared the number of failures recorded by Czech distributors in the period of increased geomagnetic activity N_h with the number of failures during the period of low geomagnetic activity N_l and with a randomly selected period N_r. The lengths W and number n_i of these three types of the interval were chosen in the same way in order to have all other conditions similar. The length W is a free parameter which ranges between 10 and 200 days serve as accumulation windows for the series of power-grid disturbances. In the case when increased geomagnetic activity on average induces a subsequently larger anomaly rate of power-grid devices, we would expect the relation

$$N_h > N_l \tag{1}$$

Even when some relation holds, its statistical significance must be tested, for which we use the binomial test.The binomial test states the probability P that the registered differences between two of N_h, N_l, N_r are in accordance with the model. Our model is the reversed hypothesis, that says there is no difference between the number of failures registered in the periods around local maxima of activity, local minima of activity, and the randomly selected intervals. If P is lower than 5% (our selection of the statistical significance), then we reject the reversed hypothesis. In such a case, we obtained an indication that indeed, there is a statistically significant increase in failure rates after the maximum of the geomagnetic activity. P is computed as

$$P_{\mathrm{h,l}} = 2\sum_{k=x}^{n} \binom{n}{k} p^k (1-p)^{n-k} \tag{2}$$

where for testing the pair N_h and N_l, $n = N_\mathrm{h} + N_\mathrm{l}$ denotes the total number of failures in two sets of chosen intervals. The parameter p states the model-expected probability of the disturbance occurring during the high-activity intervals. In the tested (that is in the reversed) hypothesis we assume that the probability of the disturbance occurring during the maximum or the minimum be the same, i.e. $p = 1/2$. Finally, $x = \max(N_\mathrm{h}, N_\mathrm{l})$. Analogous relations may be written for pairs N_h and N_r and N_r and N_l.

To quantify the difference in the failure rates for both different situations (minima and maxima of the geomagnetic activity) we evaluated a relative risk. The relative risk R is a value coming from the case-control analysis. The relative risk is 1 if there is no difference between the two groups differing in the causal attribute (in our case the casual attribute is exposure to increased geomagnetic acitity). If $R < 1$ then more often positive cases occur in a group without a causal attribute (i.e. contrary to expectation), if $R > 1$ then positive cases occur more often in a causal attribute group.

The two tests described above may give us an indication of a statistically significant increase in the failure rates in the periods of the increased geomagnetic activity. These tests still do not prove the causal link, the binomial test is an "advanced correlation measure" to some extent.

If the increased failure rates are indeed caused by the increased geomagnetic activity, where a positive but unknown time lag may play a role, one would expect that the failure rates will be larger after the geomagnetic activity maximum than before. Thus we compared the number of disturbances in the intervals of length W immediately before the local maximum with the number of disturbances in the intervals of the same length placed immediately after the maximum. We compared the mean daily failure rates in the two intervals (we would expect the mean to increase after the local maximum), the relative mean increase in the units of standard deviation of the daily failure rates, and of course we ran a binomial test evaluated by (2) to test the statistical significance.

A similar comparison was done for the minima. For the minima, we do not expect a significant change in the failure rate before and after the minimum.

Results of this study were published in a paper [15]. We found that in the case of the datasets recording the disturbances on the power lines with the high and very high voltage levels and disturbances on electrical substations, there was a statistically significant increase of failure rates in the periods of maxima of geomagnetic activity compared to the adjacent minima of activity. There are hints that the disturbances are more pronounced shortly after the maxima than shortly before the maxima of activity Table 1. It showed up that 4 - 7 % of all anomalies can be attributable to increased geomagnetic activity. Anyhow, we still do not know much about the causality.

In this manner, we modelled the geoelectric field using one-minute geomagnetic measurements from Intermagnet database. We applied this model to the long-term measurements of the geomagnetic field during the period of increased solar activity (for example in days when the aurora was observed) and considered possible destructive effects on the distribution network infrastructures.

What we practically do is:

- we ignore Earth's surface curvature,
- we establish a Cartesian coordinate system where x points northward, y points eastward and z axis points downward,
- we assume plane wave propagation of electric and magnetic fields along the z axis,
- we consider the ground as an infinite half-space with a uniform conductivity.

Having an assumption of harmonic time dependence with angular frequency ω then it can be shown that the horizontal geoelectric field component E_y is related to the x component of variation of the geomagnetic field ($\frac{\partial B_x}{\partial t}$) by the equation

$$E_y = -\sqrt{\frac{\omega}{\mu_0 \sigma}} \exp^{i\frac{\pi}{4}} B_x. \tag{3}$$

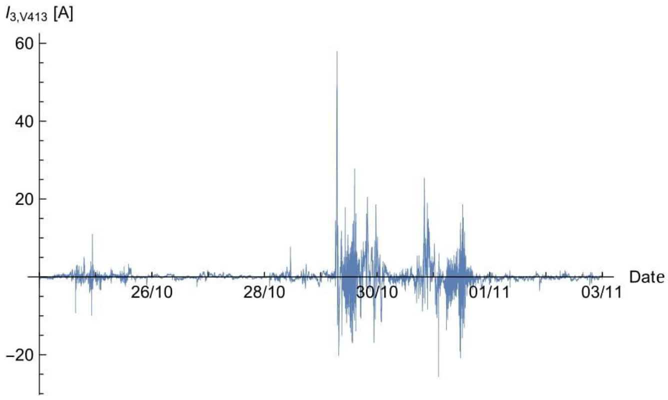

Figure 1. Computed GIC for one transmission line V413 in west–east direction with lenght of 284km during the Halloween storm in 2003.

The decrease of the conductivity and the increase of the angular frequency increases the geoelectric field with respect to the geomagnetic field.

Time derivative of $B_x(t)$ in Fourier space gives $i\omega B_x$ which can be seen in (3). After application of an inverse-Fourier transform we get integro–differential equation coupling electric and magnetic fields

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}}\int_0^{\infty}\frac{g(t-u)}{\sqrt{u}}du \tag{4}$$

in time domain, where $g(t) = \frac{dB_x(t)}{dt}$. It is in agreement with causality which means that at the time t $E_y(t)$ depends only on the previous values of $g(t)$. Weight of affection by past values decreases with time. A stable solution can be achieved by integration over several hours. The calculation can be done either in time or frequency domain. Correspondingly we can compute $E_x(t)$.

However, the square root in the denominator has a singularity at $t = 0$. This problem is caused due to quasistatic approximation, where displacement currents are ignored. We were dealing with this situation in a way of using a different model of the time evolution of the magnetic field using linear interpolation between discrete data. Details of this method can be found in [16].

Moreover, A.Smičková computed GIC using our geoelectric field for two (east–west and north–south oriented) high voltage transmission lines in the Czech Republic (see Figure 1) and found surprisingly high values of currents in the order of tens of amperes [18] .

4 Concluding Remarks

Our results provide an evidence that the geomagnetically induced currents may affect the occurrence rate of anomalies registered on power-grid equipment even in the mid-latitude country in the middle of Europe. A follow-up study that includes the modelling of GICs is needed to confirm our findings.

In the outcoming paper [17], we studied responses of power lines and transformers in the Czech electric power grid to geomagnetic storms. We tried to estimate the time delay between the spikes of geomagnetic activity during storms and substorms described by DST, $SYM\text{-}H$ and AP indices and the following response of the Czech electric distribution grid. We used superposed epoch analysis to determine the response of disturbance rates with respect to peak in the geomagnetic activity. For the disturbances recorded on the power lines, the anomaly rates increase appreciably almost immediately (within a day). On the other hand 2–3-day delay has been found for transformers. We show that about 1–2 % of the anomalies in the Czech power grid were probably related to exposure to GICs.

Currently, we are trying to support our findings with case studies of specific CMEs and we study their effects on the magnetosphere, on the response of geomagnetic field and on the anomaly rates in power grid. We also plan to apply a reverse approach where we start with looking for the periods of increased anomaly rates and afterwards we will match this significant increase with a posiible CME. This method may tell us more about the properties of CMEs with the highest geoeffectivity.

Dataset ID	Intervals	N_h	N_r	N_l	$P_\mathrm{h,l}$	$P_\mathrm{r,l}$	$P_\mathrm{h,r}$	a	b	c	d	R	I_r
D1	7	34	24	16	0.01535	0.23705	0.26819	34	316	16	334	2.125	< 0.01
D2	4	53	36	42	0.30489	0.08932	0.57159	53	147	42	158	1.2619	–
D3	4	7	5	11	0.48068	0.77441	0.21011	7	193	11	189	0.63636	–
D4	4	10	16	13	0.67764	0.32694	0.71107	10	190	13	187	0.76923	–
D5	4	27	24	21	0.47088	0.77977	0.76599	27	173	21	179	1.28571	–
D6	4	17	8	10	0.24779	0.10775	0.81453	17	183	10	190	1.7	–
D7	9	89	4	31	$< 10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	89	361	31	419	2.87097	0.62
D8	7	405	331	373	0.26638	0.00709	0.12223	228	122	199	151	1.14573	–
D9	7	33	35	39	0.556	0.9036	0.72755	31	319	33	317	0.93939	–
D10	7	6239	5858	5230	$< 10^{-5}$	0.00055	$< 10^{-5}$	350	0	350	0	1.0	0.13
D11	7	203	195	85	$< 10^{-5}$	0.72573	$< 10^{-5}$	140	210	69	281	2.02899	0.65
D12	7	5035	4637	3990	$< 10^{-5}$	5e-05	$< 10^{-5}$	349	1	349	1	1.0	0.19

Table 1. Statistical analysis of disturbances in the Czech distribution network for the 50-day window. For datasets D1–D12 we give the number of interval pairs, the total number of reported disturbances in the periods of increased activity, decreased activity, and in the random intervals. Then we give the probabilities P with which the differences in the number of failures between two intervals are due to chance. In the last section we give necessary values for the computation of the relative risk R and also the value of I_r.

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