

Comments from referee #4

General Comments

This paper extends previous investigations into understanding the impacts of induced electric fields and GICs on Sweden's power grid for extreme geomagnetic storm scenarios. The study utilises results generated from models described and published in previous works. The text and figures are generally of high standard, however, given the reliance of models cited in previous works, the paper could benefit from a little more detail regarding these to make this paper more self-contained. There are also some statements/concepts that require further qualification and/or clarification. The following general comments are followed by specific comments that should be considered by the authors to improve the overall readability.

We thank the reviewer for a critical review and helpful comments. We have done our best to reply to each concern. The original review is written in black and our replies in red. The line numbers refer to the original version of the manuscript.

Although the authors do state the following with regards to Case 2, "*In the second case (Case 2), we construct an idealized scenario in which the magnetic field time series is spatially uniform across all magnetometer stations.*", the paper could benefit from a little more qualification early in the paper of why this approach was taken. It is acknowledged that the benefit becomes apparent later in the paper, particularly for southern Sweden, however, early qualification would improve the readability.

We thank the referee for this comment. We agree that an early qualification would improve readability. We have added a few sentences at the beginning of the Method section, in line 105:

Our motivation for scaling the geoelectric field was that it is the physical driver of GICs. Using real ground-magnetic perturbations as input preserves a realistic ionospheric forcing (rather than relying on a synthetic magnetic-field time series), while the scaling ensures that the resulting electric field reaches the level associated with a 1-in-100-year event from the perspective of the physical driver of GICs. This allows us to generate as many worst-case scenarios as magnetic field inputs are available. However, because ground magnetic perturbations are driven by ionospheric current systems that activate during geomagnetic storms and substorms, we recommend using magnetic-field inputs from previously recorded events that produced the largest geoelectric field response.

To illustrate the range of possible worst-case conditions, we explore two complementary approaches. The first worst-case scenario (Case 1) is intended to remain as realistic as possible, with each geographic location experiencing a different magnetic field perturbation. This is achieved by using as many magnetometers as are available in Sweden, providing a well-resolved ionospheric driver. The second worst-case scenario (Case 2) is intended to represent an idealised case in which every location in Sweden experiences the same magnetic field perturbation (i.e., the frequency content remains identical). This is achieved by using data from a single magnetometer. Such an idealised situation could be produced by a large-scale westward electrojet (WEJ) extending across Fennoscandia.

The authors use multiple terminology for storms as "strong", "intense", "severe", and "extreme". When using these different terms it should be made clear that it is with respect to a particular metric, or alternatively, use consistent terminology throughout the paper. Although there is no consistent international standard definition of "extreme" storms, as noted by the authors in lines 272-273, the terms should be applied with a consistent approach within the paper.

We thank the reviewer for pointing out the inconsistent terminology. We have now adopted a consistent scheme throughout the manuscript and clarified this in Line 28:

*In this paper, we use the term **extreme** exclusively for 1-in-100-year events. All other impactful events (e.g., strong, intense, or severe) are referred to as **major** events.*

Specific Comments

Lines 7-8 and throughout: The term "electric field" is used and then interchanged with the term "geoelectric field". Perhaps better to be consistent.

Thank you for checking this. We selected "geoelectric field" to be used throughout the manuscript.

Line 8: Suggest removing "s" from "lines".

Done

Line 31: Is the ordering of references alphabetical or chronological? A consistent approach should be used.

A chronological order is used throughout the manuscript. We have corrected the citation and reviewed the full text for consistency.

Line 33: Suggest moving the "Bergin" reference to after "May 1921 storm".

Done

Lines 37-40: As per general comment, the Halloween storm (Dst minimum = -383nT) is referred to as an "extreme" storm whereas the May 2024 storm (Dst = -412nT) is referred to as "severe". Consistent terminology should be used as much as possible.

Thank you for pointing this out. We have updated the terminology to ensure consistency with our definitions earlier in the manuscript. The terms "extreme" and "severe" have been replaced accordingly. Lines 37-40 now read:

The first well-recorded major geomagnetic storm was the Halloween event of 29–30 October 2003, which reached a minimum Dst of approximately -400 nT. More recently, the major storm of 10–12 May 2024 reached a minimum Dst of about -412 nT, making it the largest geomagnetic storm since the Halloween storms of 2003 and the second largest event after the 13 March 1989 storm.

Line 58: Suggest adding "at high latitudes" after "attributed to substorms" and replace "of" with "for".

Done

Lines 73-73: Please clarify if this is electric field calculated using 1D or 3D conductivity structures.

Thank you for this observation. Lines 73-74 now reads:

[...] the event producing the largest geoelectric field in Sweden during the last two solar cycles when derived using a 1D ground conductivity model ($E_H=2.73$ V/km). This result was later confirmed by Rosenqvist et al., 2025, who reported the largest geoelectric field derived using a 3D ground conductivity model ($E_H=22.4$ V/km) for the same event over the same period. [...]

Lines 76-78: As per general comment regarding the use of multiple terminology for storms as "strong", "intense", "severe", and "extreme".

We have updated the manuscript. In the new version, Lines 76-78 now reads:

[...] This was also the first major and well-recorded geomagnetic storm [...]

Line 102: Suggest citing reference as "Rosenqvist and Hall (2019)".

Done

Lines 111-112: Can the authors provide some detail as to the extrapolation/interpolation technique used for Case 1?

We included more information about the GIC-SMAP model in section 2.2. Furthermore, we added the following clarification in line 111:

[...] we use the actual observed magnetic field perturbation interpolated using the SECS method to the whole Fennoscandian region.

Line 116: The "SECS" acronym should be defined in the paper.

Thank you for this observation. It is now included in the new paragraph describing the GIC-SMAP model in Section 2.

Lines 120-121: "However, using the external field allows estimation at locations where measurements were not collected, since it is independent of the ground conductivity." This statement needs more qualification as the paper suggests the interpolation/extrapolation is used for Case 1 and Case 2 to provide time series where measurements are not collected. What are the measurements being referred to?

Thank you for pointing this out. After reviewing the sentence in context, we concluded that it did not add meaningful information and have therefore been removed from the manuscript.

Lines 123-125: These sentences to explain "plausible" are somewhat confusing. Please consider rewording.

The new sentence in lines 123-125 now reads:

By "plausible," we refer to a geoelectric field whose magnitude peaks near the characteristic geomagnetic latitude threshold where extreme driving is expected.

Line 144: "The magnetic field components B_x and B_y time series are presented in Figure 1b,c." Although the caption of Figure1 indicates the interpolated time series are for the locations indicated by stars, this is not obvious in the text. Please indicate this in the text to assist the readability.

We have updated the text. Line 144 now reads:

The magnetic field components B_x and B_y time series at the locations indicated by a star in Figure 1a are presented in Figure1b,c.

Line 146: Insert spacing prior to hyphen in "20:02:00– 20:08:40 UT".

Done

Line 149: Insert "a" before "few".

Done

Line 153: Insert "in" before "Figure" and remove "s" from "occurs".

Done

Line 164: Suggest replacing "is illustrated" with "are provided".

Done

Figure 1a: The brown star is heavily obscured.

We changed Figure 1a to make the brown star more visible by moving the KIR label southward.

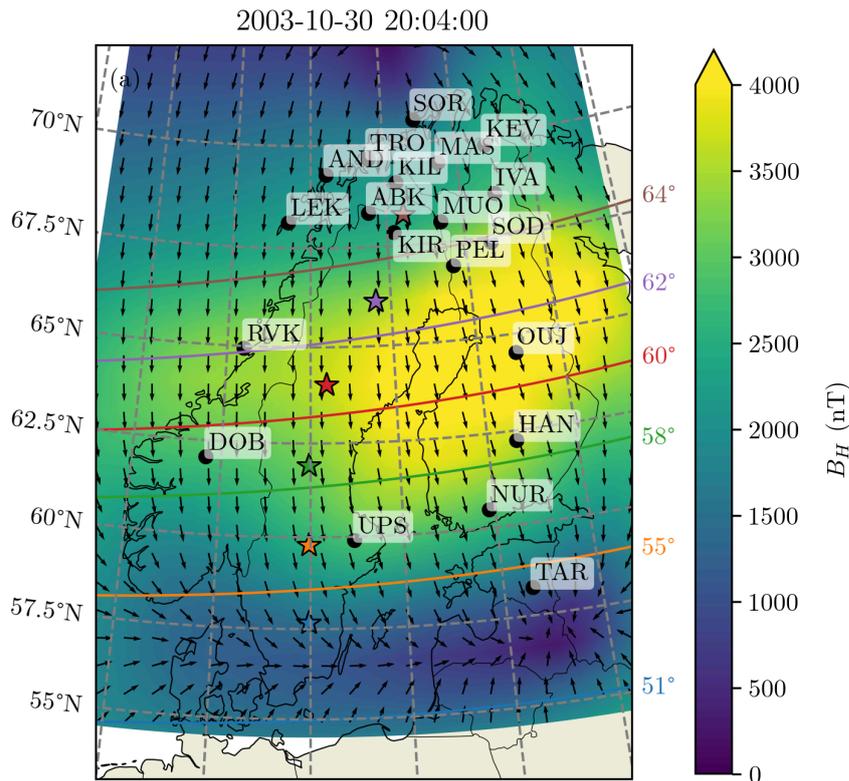


Figure 1 caption, second line: Insert "Interpolated" before "Time series"?

Done

Lines 180-181: This sentence, and the time series plots of Figure 3b (and their max values indicated by black dashed lines), are somewhat inconsistent with the statement in lines 113-114, "In the second case (Case 2), we construct an idealized scenario in which the magnetic field time series is spatially uniform across all magnetometer stations". Please clarify and/or qualify with respect to lines 113-114.

Thank you for making this important point. We agree that there was an inconsistency with the statements in lines 113-114. After reviewing the surrounding text, we found that the inconsistency originated from the preceding sentences. We have therefore revised lines 177-179 to read:

[...] In Case 2, we assume that a large-scale ionospheric current covers all Fennoscandia. The ionospheric equivalent current shown in Figure 2a confirms that a current system was indeed present, but was limited to northern and central Fennoscandia, with a maximum between Finland and Sweden. [...]

This should be later complemented with the already existing sentence in line 183-185

[...] Due to the latitudinal differences in the waveforms, we had to determine which one was most representative of the current system to later apply it across the entire region. [...]

Lines 183-185: Same comment as for 180-181, "Due to the latitudinal differences....". Please clarify and/or qualify with respect to lines 113-114.

Thank you for this comment. We consider that this sentence is now placed in a better context after the revisions made in response to the previous comment.

Line 204: "factos" should be "factors".

Done

Figure 4 caption: Is the term "ground-based observations" correct? The paper states that Case 2 uses B_{ext} from the SECS method which suggests its not directly an observation. Please clarify.

The referee is correct. We have revised the figure caption to avoid implying that Case 2 relies on direct ground-based observations. The updated caption now reads:

Case 2: Estimated 3D horizontal geoelectric field during 30 October geomagnetic storm using two different magnetic field waveform inputs. (a, d) Magnitude of the external component of the horizontal magnetic field (B_{ext}) from the OUJ and HAN stations, respectively. (b, e) magnetic field perturbations. (c, f) horizontal geoelectric field time series at the fixed locations shown with stars in Figure 1a.

Line 211: "similarly"?

This was changed due to the comment of another reviewer to:

[...] mainly dominated by the observations in HAN and OUJ, which are very similar to the input used in Case 2. [...]

Figure 5 caption, second line: "Shows" should be "shows"?

Done

Line 224 and throughout: The power line voltage is described as voltage per km which is effectively electric field. Is this the average electric field over the length of the power line? Some information regarding how this is calculated would help with readability. Further, how were the thresholds of 1 V/km and 3 V/km determined to indicate hazardous conditions?

Thank you for this valuable comment. We have added clarification about these two parameters in Line 220:

The impact on the Swedish power grid is limited to the analysis of the induced voltages in the transmission lines, calculated by integrating the geoelectric field along the power lines under the two 1-in-100-year scenarios. To complement the total induced voltage, we also compute the voltage per kilometre, which corresponds to the line-averaged geoelectric field projected along the transmission line direction. This provides a measure of the effective geoelectric driving experienced by each line, independent of its length. We acknowledge that this does not represent the full behaviour of the Swedish power grid as a connected network. However, large induced voltages (Voltages > 100 V) have been related to several issues during the March 1989 geomagnetic storm(Lucas et al., 2018).

With respect to the thresholds 1 V/km and 3 V/km, these were initially selected to represent low and high maximum voltage per km during the substorm event. To better define these limits, we used the 20th and 80th percentiles of the maximum voltage per km in each case:

Case 1: $P(20) = 1.17$ V/km; $P(80) = 3.34$ V/km

Case 2: $P(20) = 0.75$ V/km; $P(80) = 2.76$ V/km

All text and figures related to these thresholds have been updated in the new version of the manuscript.

Figures 6c and 7c: The figures appear to omit lines between 1-3 V/km? Is this correct? Would it have been better to use a different colour for lines between these thresholds?

Thank you for this comment. The omission of lines with maximum values between 1 V/km and 3 V/km (now 20th and 80th percentiles) is intentional. Our aim in Figures 6c and 7c was to highlight only the transmission lines experiencing the lowest and highest levels of line-averaged geoelectric field (voltage per km) under the worst-case scenarios. Showing only lines below 20th percentile and above 80th percentile allows us to emphasize the extremes in the system without visually overloading the figures.

Lines 241-244: This needs a little more qualification here by referring to Figures 6 and 7. The results of this paper suggest that Karlshamn is not vulnerable to the extreme scenario in Case 1 and appears to be missing from Case 2, perhaps as per the previous comment. It is acknowledged that these statements are somewhat qualified later in the paper (lines 363-364) but qualification here would help with readability.

We thank the reviewer for this valuable comment. We have extended our interpretation about the situation in Malmö and Karlshamn substations. Lines 237-244 reads now:

Interestingly, Malmö, which experienced a GIC-induced blackout in 2003, does not appear as a major hotspot in the Case 1 results. This may be attributed to the limited magnetometer coverage in southern Sweden ($MLAT < 55^\circ$) during the Halloween event, as well as uncertainties in the regional conductivity model. Notably, Malmö is identified as vulnerable under Case 2, when a large-scale ionospheric current system is assumed.

A particularly noteworthy case is Karlshamn, which appears susceptible to GICs even under relatively low E_H values, between 0.42~V/km and 0.75~V/km, according to Table 1 in Rosenqvist et al., (2025). As with Malmö, this behaviour may be influenced by sparse magnetometer coverage in southern Sweden and by limitations in the conductivity model. In addition, the most intense GICs are often observed at substations located near the edges of a power-grid network (Viljanen et al., 2012). Both Malmö and Karlshamn lie along the southern boundary of the Swedish transmission system, which may enhance their vulnerability. These examples highlights how local grid topology and substation characteristics may influence vulnerability independently of regional E_H strength.

Figure 7 caption: Should be "(b-d)"?

Done

Lines 263-265: The authors acknowledge that other parameters are needed to convert the estimated voltages to current flowing through the transmission lines and transformer windings in the network to understand the impact of GICs. Although the estimation of voltages is of value, longer lines in general will have higher total resistances (an analogous plot to Figure 8c of line length to total resistance would be similarly linear). The nominal operating voltage of these lines are hundreds of kV with operating tolerances typically of 5-10%. Statements such as those in lines 263-265 and lines 326-327 should be qualified more definitively using industry standards in terms of line tripping and network impact.

We thank the reviewer for these very important points. In the revised manuscript, Lines 263-265 have been removed and we included the following text in Line 318:

[...] We have shown that during intervals of very active ionospheric current variations, particularly during substorm activity, large dB/dt and E_H values were estimated at latitudes below 60° MLAT. As a consequence, several power lines exceeded high voltage thresholds (e.g., approximately 100 power lines experienced induced voltages exceeding 50 V at several times during the substorm period). For comparison, Lucas et al., (2018) reported that 62 transmission lines exceeded 100 V during the March 1989 geomagnetic storm, which triggered a major blackout in the Hydro-Québec power system. Although power grid disturbances do not always coincide with the time of peak voltage or geoelectric field (Dimmock et al, 2024, Wallner et. al., 2025), or with peak GICs (Pulkkinen et al., 2005), intervals of high induced voltages still imply larger voltage variations.

We modified the text in line 326, now reads:

[...] The large number of power lines subjected to high induced voltages in our scenario could lead to elevated GICs, which in turn may affect protection relays. Relay misoperations are often linked to harmonics, inappropriate relay types or settings, or faulty relay systems, rather than to the voltage magnitude itself. Collapse can be initiated by one or several coincident relay misoperations, each removing a transformer or line from service while its integrity is verified. Based on this, relay actions may occur during intervals of high or rapidly changing rates of change voltage rather than strictly at maximum voltage.

Understanding which combinations of geoelectric field, induced voltage, network configuration, and system state lead to real incidents remains an open problem and requires further investigation. Such studies will soon be possible with the recently installed GIC monitoring device in Karlshamn, connected to the transformer neutral-to-earth point and deployed by the Swedish transmission system operator, Svenska Kraftnät.

Line 291: Suggest replacing "area" with "range".

Done

Line 294: Suggest using "cables" or inserting "the" before "telecommunication".

We have used cables.

Line 301: Although the MLAT threshold for the Pulkkinen et al study was provided early in the paper, perhaps it would be useful to provide again for context here.

We agree with this comment. We included the following clarification in line 301

MLAT threshold (i.e., the magnetic latitude where maximum geomagnetic disturbances and geoelectric fields typically occur)

Lines 310-313: The numbers appear to be quoted as resistances in Ohms but their low values would suggest they are resistivity. Please clarify. If they are resistance values then it would not seem appropriate to apply for all transmission lines as their resistance is a function of resistivity, length and area. Are these values used in the RAISE model or are they determined from applying these resistance values to the obtained voltages? Please provide more information on how the currents were calculated to qualify the estimates of 200 A.

Thank you for pointing this out. The values in Line 311 refer to line resistances per unit length $r_{L,220}=0.022 \Omega/\text{km}$ and $r_{L,400}=0.008 \Omega/\text{km}$ have been corrected. These values have been used by Viljanen et al., (2012) and later implemented in the RAISE model (Rosenqvist et al, 2025).

The value of 200 A mentioned in the manuscript is not derived from our voltage estimates. Instead, it reflects an operational guideline communicated privately by Svenska kraftnät regarding the GIC levels that can be of concern for transformer performance in the Swedish grid.

Lines 365-367: Should this statement be clarified for Case 1 as Case 2 does suggest Malmo is vulnerable?

Thank you for this comment. We have clarified that that statement is for Case 1.

Line 372: Should the reference citation be "Vanhamaki and Juusola, (2020)"?

Yes, the citation was corrected.

References: Some reference titles use capitalisation and others don't. Should this be consistent?

All references have been reviewed to be consistent.