Reply to Referee #2

Liisa Juusola[1], Ari Viljanen[1], Ilja Honkonen[1], Magnar Gullikstad Johnsen[2], Andrew Dimmock[3], Vanina Lanabere[3], and Alice Wallner[3]

[1]Finnish Meteorological Institute, Helsinki, Finland.
[2]Tromsø Geophysical Observatory, UiT The Arctic University of Norway, Tromsø, Norway.
[3]Swedish Institute of Space Physics, Uppsala, Sweden.

Correspondence: Liisa Juusola (liisa.juusola@fmi.fi)

We thank Referee #2 for constructive comments and agree with almost all of them. Please, see below for our point-by-point replies. The original review is written in *black* and our replies in blue.

The authors present an interesting study expanding on previous efforts to describe the geoelectric field using divergence-free (DF) and curl-free (CF) Helmoltz decomposition. This provides important intuition about the role of the source and telluric currents and could be used more widely in other geoelectric and GIC studies.

General comments:

It should be made more clear (especially on Lines 79–80 when you lay out the outline of the paper) that you first undergo a validation effort for your modelling using a geomagnetic storm from 1998 before moving on to the specific results for the May 2024 storm. It is confusing for the reader to see the title about May 2024 in Northern Europe, but then Section 2.1. 2.2, and 2.3 are all about June 1998 storm.

We suggest to modify this section as follows: "The structure of the study is as follows: the data and methods are described in Section 2. We will take advantage of the unique BEAR network measurement campaign in 1998 to both illustrate and demonstrate the validity of our methods. The actual results obtained by studying the May 2024 storm are presented in Section 3. In Section 4 we will discuss the recipe for intense GIC production as well the limitations and advantages of out method. The conlusions are summarised in Section 5."

Recommend to either remove Section 2.4, Section 3.4 and Figure 12, or mention that Central Europe will be investigated in the abstract and title. As it is written, these sections seem out of place in the context of a paper which primarily focuses on Fennoscandia.

We will remove section 2.4, section 3.4, and Figure 12.

Line 9: I strongly disagree with this assessment that 1 min E_DF can be used as a "reasonable proxy" for GIC. Your results show large variations in peak GIC depending on the choice of method which, without GIC data validation, makes it very difficult to assess which E field model is preferable. For example, the 60 s DF underestimates the 10 s DF+CF |GIC| by a factor of 5 at Alajarvi. Similar discrepancies are seen at other sites in Table 1 as well as in Figures 7–10. From a hazards perspective, a factor of 5 in GIC is a significant difference in risk to transformers and other relay equipment. If the 10 s CF+DF can be validated against GIC measurements as being the more accurate method, then it highlights the need for higher cadence magnetic datasets, and the necessity of incorporating ground conductivity into GIC modelling. (Note that there are also cases which see extreme reductions in GIC when using 10 s CF+DF compared to 60 s DF, so it is not a clear one-to-one correspondence where one method always sees higher risk; rather it is a complex story that can only be properly addressed using GIC data for validation.).

We suggest to rewrite the end of the abstract as follows: "We compare the resulting GIC in the Finnish benchmark power grid and conclude that while $\boldsymbol{E}_{DF}$ determines the overall direction and level of GIC activity in the power grid, $\boldsymbol{E}_{CF}$

can produce localized enhancements that can significantly modify the GIC amplitudes at nearby substations for certain directions of the $\boldsymbol{E}_{DF}$. The ionospheric equivalent currents provided by the SECS method yield information on the external drivers of the GIC peaks. The adaptable triangular grid for the SECS method provides a robust tool for optimal analysis of ground-based magnetometer data, scalabale to both regional and global magnetometer distributions."

Line 54-55: The way you have written this implies that the ground conductivity does not impact the divergence-free field. However, I think it is important to clarify that both DF and CF electric fields depend on the ground conductivity implicitly. The ground magnetic field measurements are a superposition of the primary ionospheric source magnetic field and the secondary induced magnetic field. Thus, the total ground magnetic field used in Equation 1 already implicitly contains information about the ground conductivity via the secondary induced field.

We suggest the following modification: "The only input needed to estimate $\boldsymbol{E}_{DF}$ are magnetic field observations. The ground magnetic field measurements are a superposition of the primary ionospheric source magnetic field and the secondary induced magnetic field. Thus, the total ground magnetic field used in Eq. 1 implicitly contains information about the ground conductivity via the secondary induced field."

Section 2.4: This seems out of place in the context of this paper.

We will remove this section.

Line 142: I think it is a typo and E_DF should be E_CF.

We suggest to remove "driven by $\boldsymbol{E}_{DF}$".

Line 164: Specify whether the 1-D model was constructed by you via some inversion method, or cite the relevant authors that produced it.

We will remove this section.

Line 223: Don't use the word "data" to refer to modelled electric field and be clear about the distinction between GIC versus E. It should read: "The majority of the peak GIC values calculated from 10 s |E| model and all peak GIC values calculated form 10 s |E_DF| model occurre..."

We will correct the text as suggested.

Line 225: Was there no available GIC data during the May 2024 storm? I am surprised if Finland does not have any active GIC monitoring.

There is no publicly available GIC data from Finland during that event.

Line 250: The geoelectric field is not dominated by longer periods. It tends to have higher frequency content compared to the geomagnetic data. This can be explained by standard MT equation E = ZB where Z is a high-pass filter. There are many examples where lower sampling rate of 1 min geomagnetic data will miss spikes in geoelectric field driven by higher frequency dB/dt. See Trichtchenko (2021) for discussion.

Compared to the magnetic field variation (B), the electric field has higher frequency content. However, we prefer to consider dB/dt, which is also more explicitly related to E (and GIC) than B.

We agree with Trichtchenko (2021) who states that "The underestimation of peak electric field with use of 1 min magnetic data ranged from ∼60% to 80% of that estimated with 10 s data, depending on the geomagnetic storm". However, an increasing sampling rate decreases dB/dt values relatively clearly more (Pulkkinen et al., 2006) (Fig. 9). In some specific cases, especially sudden commencements, the sampling rate matters very much, and even 10 s data can then miss significant features (Juusola et al., 2023) (Fig. 14).

We suggest to modify the text as follows: "The geoelectric field, on the other hand, is an inductive, conductivity-filtered response and therefore slightly less sensitive to the sampling rate."

Line 275: Is there a geological reason why the total E field is amplified in southern Finland compared to the DF field?

Korja et al. (2002) discuss geological reasons for the (laterally) highly varying conductivity in southern Finland. They are reflected as strong local enhancements of the electric field (cf. also Marshalko et al. (2023).

Line 293-297: I would remove this paragraph. It feels extremely speculative to guess why the Norway station tripped given that it is an entirely different network topology. Keep in mind that the TE mode electric field parallel to the coast would be decreased by the inductive ocean effect. Transmission lines parallel to the coast would thus see a "reverse coast effect" with a reduced electric field and reduced GIC. See Cordell and Unsworth (2025) for discussion of this.

We will remove this section.

Line 298-399: Everything in this section thsu far has shown that the 1 min data and DF field might be significantly underestimating the GIC at many locations. You also never make a direct comparison between 10 s CF+DF and 60 s CF+DF. That comparison would more definitively show the impact of 10 s versus 60 s data for the total field. But I largely disagree with your conclusion that 1 min data are sufficient.

We suggest to add 60 s CF+DF to Fig. 7a and Fig. 8a and to modify the text as follows: "Thus, we can conclude that, in the absence of ground conductivity information and higher-cadence magnetic field observations, 1 min magnetic field observations alone can, in most cases, provide a reasonable proxy for the possibility of intense geoelectric field and GIC activity in a power grid."

Figure 11: Is there a reason why you expand the region of interest to a much larger area of the North Atlantic and eastern Greenland? Previous figures have focused on Fennoscandia where magnetometer coverage is dense. If you expand to include such a large area then there is extremely sparse magnetometer coverage over most of the map area shown in Figure 11 which might make SECS much less reliable. The text in Section 3.3 seems to focus mostly on interpretation over Fennoscandia, so why not just show the area you discuss in the text and the area that has good coverage?

We want to show that the method we introduce in this paper is applicable in any spatial scale. Of course, sparse ground-based observations create more uncertainty. Also, $\boldsymbol{E}_{DF}$ tends to have such large-scale structures that interpreting them is difficult if only a small area is shown.

Line 373: This sentence about the importance of E_CF in determining GIC amplitudes should be highlighted more prominently in the abstract. In order to do a proper GIC hazard analysis, you cannot ignore galvanic effects.

We will do as suggested, please see our reply to the comment concerning "Line 9".

Line 374-375: There is a tendency to assume that the "external" and "internal" mathematical representations from SECS are a perfect mapping of ionospheric and telluric currents. In reality, the external and internal components may not be accurate representations of what is actually happening physically.

We suggest to modify the text as follows: "$\boldsymbol{E}_{DF}$ comprises an external part due to time-varying ionospheric and magnetospheric currents and an internal part due to time-varying telluric currents. In the SECS method, these are represented by external and internal equivalent currents. It should be noted that although equivalent currents produce the same magnetic field on the ground as the true currents, equivalent currents differ from the true physical currents. The external equivalent current density can be assumed to correspond to the DF part of the horizontal ionospheric current density at high latitudes."

Line 432: Disagree that E_DF can provide reasonable proxy for GIC hazard when it has 5 factor variance from other (potentially more accurate) methods which incorporate E_CF.

We suggest to modify the conclusions as follows:

1. While $\boldsymbol{E}_{DF}$ determines the overall direction and level of GIC activity in the power grid, $\boldsymbol{E}_{CF}$ can produce localized enhancements that can significantly modify the GIC amplitudes at nearby substations for certain directions of the $\boldsymbol{E}_{DF}$.

2. Polarization of the geoelectric field due to lateral variations in ground conductivity can produce intense GIC (e.g., five-fold compared to $\boldsymbol{E}_{DF}$) at substations connected to transmission lines traversing regions of enhanced geoelectric field.
3. The ionospheric equivalent currents provided by the SECS method yield information on the external drivers of the GIC peaks.
4. Adopting the adaptable triangular grid for the SECS method provides a robust tool for optimal analysis of ground-based magnetometer data, scalabale to both regional and global magnetometer distributions.
5. In the absence of higher-cadence magnetic field observations, $1\ \mathrm{min}$ data provides a reasonable proxy for the possibility of intense $\boldsymbol{E}_{DF}$, in agreement with Pulkkinen et al. (2006) and Grawe et al. (2018). Although very short-term spikes ($\sim$1 s–10 s) are certainly significantly underestimated or even missed, cumulative effects such as slow heating of transformers could maybe be estimated with $1\ \mathrm{min}$ data.

Line 434: 1 min data is not sufficient to capture rapid variations in the electric field of interest to power networks via harmonics and transients. The most notable effects seen are often associated with sudden, rapid variations <1 min.

Please see our reply to the previous comment.

Line 436: Conclusion number 3 appears to contradict conclusion number 1.

Please see the suggested modified conclusions above.

Line 441-444: In order to assess the long-term risk, you need the full geoelectric field. Using the E_DF which potentially underestimates the risk by a factor of 5 is not sufficient for hazard analysis.

$\boldsymbol{E}_{DF}$ can work as a relative indicator: when calculated at a given location, its values can be normalised with respect to the overall maximum. We suggest to modify the text as follows: "Because $\boldsymbol{E}_{DF}$ is much smoother spatially than $\boldsymbol{E}$, and fast to calculate, it could also be useful as a tool for assessing long-term GIC risks relative to a benchmark event."

References

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