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Review Article

Geomagnetically Induced Currents: Review, Impact, and Mitigation Strategies

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Abstract - *Geomagnetically Induced Currents (GICs) from space weather can adversely impact electrical grids, pipelines, railways, and other conducting infrastructure. This systematic review synthesizes 25 recent studies to survey the current knowledge on GIC generation mechanisms, documented impacts, and mitigation strategies. GICs emerge from complex interactions between geomagnetic storms, the geoelectric field, and power grid topology, requiring advanced modeling to better predict. Transformer saturation appears to be the predominant grid impact, potentially causing voltage instability and equipment damage. Pipelines may also suffer accelerated corrosion. Proposed mitigation approaches include installing blocking devices, improving forecasting, and tailoring hardware design. However, significant gaps remain regarding GIC effects on emerging grid technologies, validation of models with measurements, optimal mitigation prioritization, and risk assessments incorporating cost-benefit tradeoffs. Realizing GIC-resilient infrastructure will require coordinated efforts across the space science, engineering, economic, and public policy domains. This review summarizes foundational GIC concepts while highlighting critical research questions to aid in managing this natural hazard as reliance on technology grows.*

Keywords - *Geomagnetically Induced Currents, Power Grids, Pipelines, Mitigation, Modelling.*

1. Introduction

Geomagnetically Induced Currents (GICs) are electrical currents that pass through the Earth's surface due to interactions between geomagnetic storms and the Earth's magnetic field. Solar flares and Coronal Mass Ejections (CMEs) are two examples of solar activity that disrupt the magnetosphere and cause these storms. A geomagnetic storm is characterized by intense magnetic fields and energetic particles interacting with the Earth's magnetic field. This interaction causes electric currents in the Earth's ionosphere and magnetosphere, which travel to the planet's surface via conductive objects such as pipelines and power lines. Understanding and analyzing these GICs is critical because they pose significant risks and issues to various technological systems and infrastructures.

GICs must be investigated since they can potentially disrupt critical infrastructure systems, including power grids. GICs can harm power transmission and distribution systems, resulting in several difficulties, such as transformer heating, voltage instability, and equipment damage. Broad-scale blackouts have historically been caused by catastrophic GIC occurrences, such as the 1989 Hydro-Québec blackout, which affected millions of Canadians. The GIC risk to the power transmission infrastructure in the United Kingdom is investigated using an example of a geomagnetic storm during which GICs were suspected of producing aberrant transformer behavior [1]. The Hourly Standard Deviation (HSD) in the north or east horizontal component, a simple indicator of the strength of the magnetic field shift, is used to estimate the overall threat of rapid magnetic fluctuations to the UK power system, taking season and local time into account, and uses the time domain electromagnetic field to detect the source and small-scale anomalies. This modeling is critical for predicting the dangers associated with Geomagnetically Induced Currents (GICs). The impact of geomagnetic storms on subterranean oil pipelines is investigated using geomagnetic data in [2].

Understanding GICs is essential for several reasons.

1. Vulnerability of Power Grids: Power grids are heavily interconnected networks that span broad geographic areas. GICs can infiltrate power transmission lines and flow through transformers and other equipment via grounding connections. This can induce transformer saturation, resulting in increased warmth and potential failure. Engineers can create solutions to preserve power grid infrastructure and limit the risks associated with geomagnetic storms by analysing GICs [3].
2. Risk Assessment and Mitigation: GIC research assists in determining the vulnerability of power grids and other

vital infrastructure to geomagnetic disturbances. Researchers can construct models and tools for risk assessment by studying the features and behavior of GICs, allowing utilities and system operators to execute suitable mitigation techniques. These are examples of improved grounding techniques, transformer design improvements, or operational changes following geomagnetic storm events [4].

3. Space Weather Forecasting: Monitoring and forecasting space weather phenomena is critical for delivering geomagnetic storm warnings. Scientists can improve space weather models and forecasting methodologies by studying GICs, allowing for more accurate forecasts of the strength and impact of geomagnetic storms. This data is critical for power companies, emergency management organizations, and other stakeholders to take preventive measures and limit potential damage [5, 6].
4. Technological Advancement: GIC research helps to produce new technologies and protective measures. This includes designing and installing geomagnetically resilient equipment, improved grounding systems, and improved geomagnetic disturbance monitoring and detection technologies. Understanding GICs better may lead to constructing more resilient infrastructure capable of withstanding the effects of geomagnetic storms.

The significance of studying GICs lies in their potential risks to critical infrastructure, particularly power grids, and the need to develop mitigation strategies. By understanding GICs, scientists and engineers can work towards developing effective measures to protect infrastructure, improve space weather forecasting, and enhance the resilience of technological systems in the face of geomagnetic storms [7, 8]. The key goals of this paper are to 1) synthesize foundational knowledge across the space physics, power engineering, and risk analysis domains relevant to managing GIC hazards, 2) Highlight critical gaps where additional research is needed, and 3) provide an interdisciplinary perspective to help coordinate ongoing efforts towards GIC-resilient infrastructure.

This review makes multiple contributions towards these goals:

- Summarizes the complex space-geophysical interactions underlying GIC generation.
- Documents predominant GIC impacts like transformer saturation.
- Discusses promising mitigation approaches based on blocking devices and forecasting.
- Identifies research needs regarding emerging technologies, predictions, and optimization.

The paper is structured as follows. First, the systematic review methodology based on PRISMA guidelines is outlined. Next, key themes from the literature analysis are presented, spanning GIC generation factors, grid impacts, mitigation strategies, and gaps. The themes are substantiated using excerpts and examples from selected articles. Discussion then focuses on suggested priority areas for additional R&D coordinated across disciplines. Finally, conclusions emphasize the importance of continued GIC research and mitigation efforts to match increasing infrastructure vulnerability.

1.1. Background on GICs

Geomagnetically Induced Currents (GICs) arise from the complex interactions between energetic particles from solar storms, Earth's magnetic field, and conducting infrastructure like power grids. Changing magnetic fields generate geoelectric fields via Faraday's law of induction. The geoelectric field causes quasi-DC currents to flow through grounded transmission lines and transformers. The basic GIC generation mechanism can be summarized as follows:

Solar storm → Magnetospheric fluctuations → Geomagnetic variations → Geoelectric field → GIC flow in grids

During particularly intense geomagnetic storms, rapid magnetic field changes lasting over 30 minutes can induce geoelectric fields over 1V/km. Unlike lightning-induced transients, the slow fluctuations allow currents to infiltrate large, interconnected networks. The standard metric for storm strength is the Disturbance Storm Time (Dst) index, which quantifies deviations in the horizontal magnetic field component measured by mid-latitude observatories. More negative Dst values indicate larger storms that depress Earth's field.

A key parameter governing GIC magnitude is network geomagnetic latitude - ionospheric and magnetospheric current fluctuations more strongly influence high latitude grids situated under the auroral oval. The peak geoelectric field also depends on the local subsurface conductivity profile, which can attenuate or amplify signals.At the power grid level, GICs are assessed by their quasi-DC biasing effect on transformer cores. Half-cycle saturation from GICs causes increased hotspot heating, vibration, harmonics, and reactive power losses that can potentially damage or disrupt transformers.

2. Research Methods

This systematic review was conducted based on the PRISMA guidelines. The literature search was performed in March 2023 using the IEEE Xplore, Web of Science, and Scopus databases. The following search string was used: ("Geomagnetically Induced Current*" OR GIC) AND (Power OR Pipeline OR Infrastructure OR Effect* OR Impact* OR Mitigate* OR Strategies*). Relevant papers published since 2000 in English-language peer-reviewed journals were included. Reference lists of selected articles were screened to identify additional relevant studies.

2.1. PRISMA

A flowchart of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method displays the entire process, from looking for evidence to selecting relevant articles. It can be observed how a systematic review's search results are processed by following the stages in the PRISMA flowchart. It also details how many articles were discovered, included, and excluded, and the criteria for making those decisions. During the identification phase of a search, the PRISMA diagram shows how to use databases and other primary and secondary sources to find relevant results. We compiled 3,335 relevant documents using Google Scholar and other databases. Google Scholar contains 835 articles and 2,500 papers in the One Search database. After removing duplicates, 335 high-quality scientific articles published between 2000 and 2023 remained. The ** in the PRISMA diagram represents the route's final destination. 135 products were rejected because they did not match the criteria. After evaluating their abstracts, only 80 of the remaining 200 studies were included in the final analysis. After screening for eligibility for the qualitative review and relevance to the project, 55 full-text scholarly publications were removed. Later in this paper, we will go over the 25 articles that comprise this study's critical review.

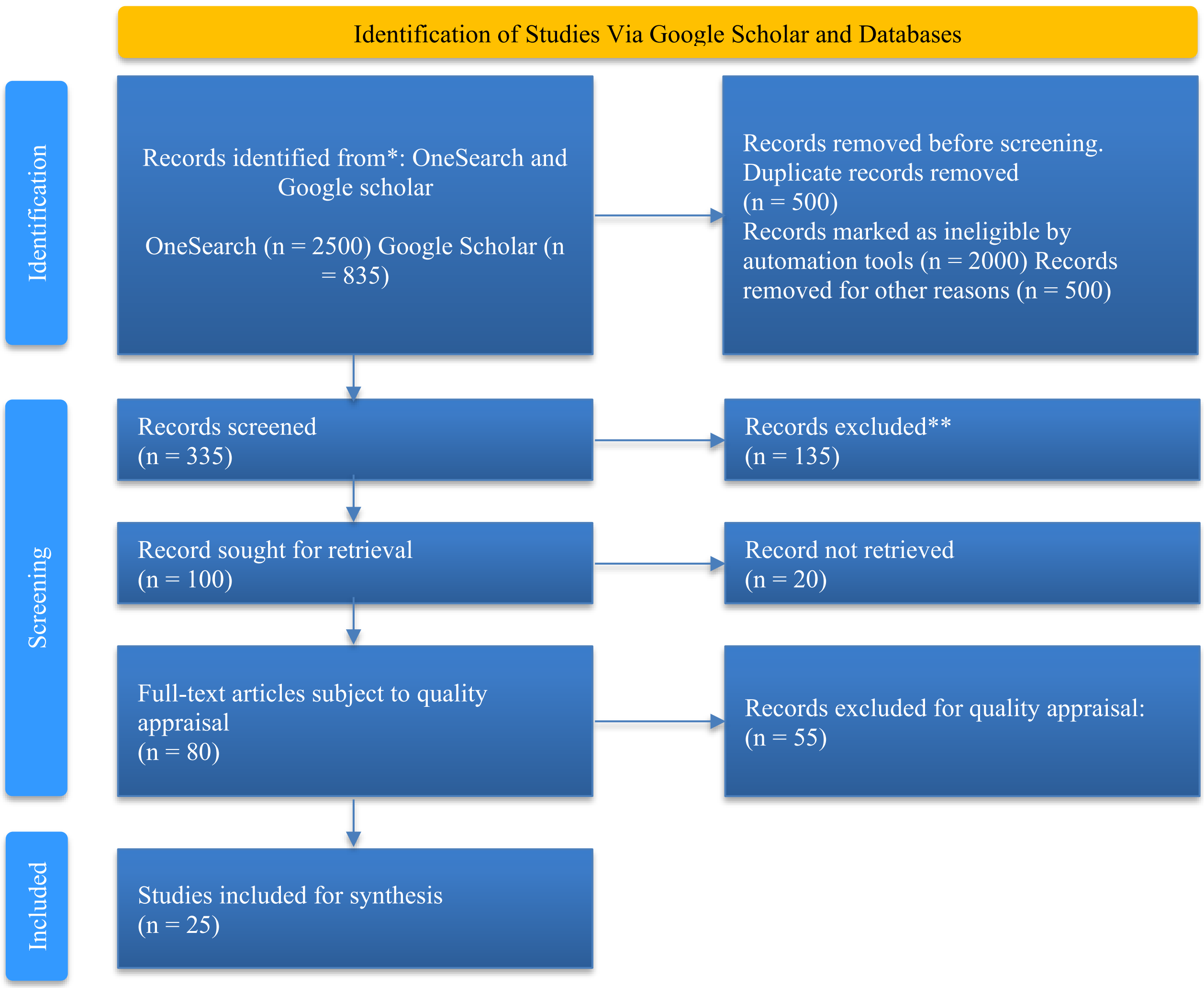

Fig. 1 PRISMA flow chart

2.2. Inclusion and Exclusion Criteria

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Publication date	2000 - present	Before 2000
Language	English	Non-English
Publication Type	Peer-reviewed journals	Conference papers, books, dissertations
Topic relevance	Primary focus on GIC generation, impacts, or mitigation	Peripheral mention of GICs

3. Results and Findings

The findings were analyzed to identify recurring themes and synthesize current knowledge within the scope of this review.

Based on a review and analysis of the selected literature, the following key themes emerged:

1. GIC generation depends on complex interactions between space weather, regional geology, and grid configurations [9-12].
2. Transformer saturation is the most widely reported power grid impact of GICs
3. Blocking devices and improved forecasting are commonly proposed mitigation strategies [13].
4. Significant research gaps remain around emerging technologies, forecasting, and optimal mitigation [14].

3.1. Theme 1. GIC Generation Depends on Complex Interactions between Space Weather, Regional Geology, and Grid Configurations

3.1.1. GIC Generation

Multiple studies have examined how geomagnetic latitude, subsurface conductivity, and network topology influence GIC generation. Locations at higher latitudes are more strongly affected by auroral ionospheric currents during geomagnetic storms, which induce larger geoelectric fields. However, soil and rock conductivity profiles play a major role in attenuating these geoelectric fields before propagating through power grids. Grid topology and orientation relative to the geoelectric field govern the network's effective "antennae" gain for collecting GICs. Complex modeling is required to account for these interconnected factors in predicting GICs. Further work is needed to integrate real-time conductivity data and detailed grid parameters into GIC forecasts [15-18].

Multiple studies highlighted that GIC generation involves complex interdependencies between space weather factors, regional geological characteristics, and power grid properties. For space weather, geomagnetic latitude and storm intensity were identified as the primary drivers of induced geoelectric fields. However, local subsurface conductivity heavily affects the geoelectric field penetration, resulting in significant geographic variability. The orientation and topology of the power network then determine the grid's susceptibility to GICs for a given geoelectric field. High-voltage transmission systems spanning long distances are most vulnerable, while distribution grids are less affected. Overall, GIC generation emerges from the complex intersection of space, geophysical, and engineering factors. Quantifying these interactions remains an active research challenge [19-23].

Specifically, the Geoelectric Field (E) depends on the rate of change of the magnetic field (dB/dt) and the local subsurface conductivity (σ) according to:

$$E = (1/\sigma) \int (dB/dt) \quad (1)$$

Regions with high conductivity shunt the magnetic field fluctuations, reducing E. During storms at higher latitudes, dB/dt and E reach very high levels. The topology of the grid then acts as an antenna to collect GICs based on Faraday's and Ohm's laws:

GIC = geoelectric field integral x grid impedance (2)

3.2. Theme 2. Transformer Saturation is the Most Widely Reported Power Grid Impact of GICs

3.2.1. Impacts on Power Grids

Transformer saturation has been extensively documented as the most disruptive effect of GICs on power grids, often leading to voltage instability and reactive power losses that can culminate in blackouts. The quasi-DC bias of GICs forces transformer cores into half-cycle saturation, causing harmonics, heating, and vibration. This can, in turn, cause false trip protection relays and cause incorrect tap changer operation. Damage to large transformers due to overheating is also a major concern. However, effects propagate beyond just transformers, with GICs also found to cause line tripping, reduced transmission capacity, and generator reactive power losses. Further study of GIC propagation through complex interconnected networks would aid mitigation [24-32].

3.2.2. Impacts on Pipelines

GIC effects on buried pipelines have been studied through field data collection and corrosion experiments. GIC flow through pipelines can accelerate corrosion by increasing the potential difference between surfaces. Severe corrosion damage called "ditching" has been documented in some cases. GICs may also interfere with cathodic protection systems and pipeline control electronics. However, questions remain regarding the sensitivity of modern pipeline designs to GIC corrosion and the applicability of laboratory studies to real field conditions. More research on GIC impacts on today's long-distance high-pressure pipelines would be beneficial [33-35]. Across the literature, transformer saturation was consistently identified as the predominant impact of GICs on power grids. Multiple field events and simulations demonstrated how DC-biased GICs can push transformers into half-cycle saturation. This leads to increased transformer heating and harmonic generation, which can cause reactive power losses, voltage instability, relay misoperations, and equipment damage. The quasi-DC GIC shifts the transformer's operating point on its B-H curve into saturation [36]:

$$B = \mu H + GIC\ x\ time \quad (3)$$

The absorbed reactive power (VAr) is given by:

$$VAr \propto GIC2 \quad (4)$$

Transformer saturation is the primary mechanism by which GICs propagate wider disturbances throughout the power network. Other equipment may be affected, but transformer effects dominate [37].

3.3. Theme 3. Blocking Devices and Improved Forecasting are Commonly Proposed Mitigation Strategies

3.3.1. Mitigation Strategies

Promising mitigation strategies exist, including blocking devices, improved designs, operating procedures, and standards implementation. However, given limited resources, a comparative cost-benefit analysis is lacking to guide optimal mitigation investments. Detailed risk assessments considering network criticality, equipment aging, and cost factors can help prioritize the most effective hardening measures. Optimal strategies will balance hardware upgrades, operational changes, and advanced forecasting.

Various measures can help mitigate GIC impacts:

Operating Procedures: System operators can take preemptive action during geomagnetic storms. Protective measures include lowering transmission voltages, canceling transformer tap changes, and increasing reactive power reserves [39, 40]. Situational awareness using GIC monitors and solar weather alerts improves response.

Blocking Devices: Series capacitors and transformers with high winding resistance (e.g., zig-zag transformers) act to block GIC flows. Locating them at the input of vulnerable equipment limits GIC propagation [41-47]. However, blocking devices are not always feasible due to high cost and grid reliability constraints.

Improved Forecasting: Advanced space weather monitoring and GIC modeling allow for better storm predictions [48]. Accurate forecasts enable operators to take preventive steps and avoid overreaction. Real-time geoelectric field measurements also help constrain GIC estimates.

Hardware Upgrades: New transformer, relay, and transmission line designs aim to reduce GIC impacts [49-51]. GIC-optimized components are less susceptible to half-cycle saturation, harmonics, and relay maloperations. However, widespread deployment is limited by high replacement costs.

Policies and Standards: Government and industry organizations have developed GIC standards and planning guides to promote resilience [52-56]. These provide risk assessment methodologies and engineering practices to counter GIC threats. Compliance incentives and regulations help drive adoption.

The installation of blocking devices and the advancement of space weather forecasting emerged as two prevalent approaches for mitigating GIC impacts discussed in the literature. Blocking devices such as capacitors suppress GIC propagation, while new transformer designs reduce saturation susceptibility. However, widespread deployment is hampered by high costs and grid stability considerations [57]. Forecasting allows preemptive operating adjustments ahead of storms, but accuracy remains challenging. The studies suggest that integrated strategies combining selective hardware upgrades, operational changes, and forecasting improvements may be optimal for GIC mitigation [58].

$$GICgrid = GICtotal \, x \, Zgrid/(Zgrid + Zblock) \quad (5)$$

Where Zblock impedes the blocking device, new transformer designs reduce saturation susceptibility through shields or tertiary windings. Physics-based models driven by solar observations are used to predict GIC levels [59]:

$$GIC = f(dB/dt, network\ model, ground\ model) \quad (6)$$

The studies suggest that integrated strategies combining selective hardware upgrades, operational changes, and forecasting improvements may be optimal for GIC mitigation [60].

3.4. Theme 4. Significant Research Gaps Remain Around Emerging Technologies, Forecasting, and Optimal Mitigation

Many studies highlighted critical knowledge gaps around GIC effects on newer technologies, forecasting capabilities, and optimal mitigation prioritization. As power grids evolve with renewables, storage, and smart grid technologies, GIC vulnerability remains uncertain. Current forecasting also struggles to provide actionable regional predictions.

Finally, research on where mitigation investments should be targeted to maximize resilience and minimize costs is limited but needed to guide operators. Addressing these knowledge gaps through interdisciplinary efforts is vital [24-28, 61].

Due to limitations in ground conductivity data and measurement assimilation [29]:

RMSE = f(ground model uncertainty, measurement availability) (7)

Cost-benefit analysis can help identify critical mitigation locations [30]:

Value = Resilience Improvement / Cost (8)

Addressing these knowledge gaps through interdisciplinary efforts is vital for managing GIC risks in the future [31]. The findings table based on data extracted from selected articles is given below:

Table 2. Findings Table based on selected articles

Study	Methodology	Sample/Duration	Key Findings	Significance	Limitations
Taran et al. 2023	Modeling	Simulations	Latitudes above 50° are most affected by GICs. Over 50% GIC increase during storms.	Demonstrated the importance of high geomagnetic latitudes in driving larger GICs.	The modeling was not validated with measurements from an actual affected grid.
Behdani et al. 2021	Simulations	Test system	GICs can cause ferroresonance in series-compensated networks, leading to overvoltages.	Showed that GICs can drive a little-studied resonance phenomenon that threatens grid stability.	A simplified test case grid may not fully capture complex interactions in large real-world networks.
da Silva Barbosa et al. 2015	Modeling	Brazil grid	Mapped spatial variability of GICs in Brazil, with coastal regions most affected. Over 20% of lines exceeded rated GICs.	The first study of GIC risk for the Brazilian grid provides insights into regional behavior that can inform mitigation.	The analysis is limited to a single network model without benchmarking against measurements from actual events.
Feng et al. 2023	TEC data analysis	2000-2020	A positive correlation was found between global TEC and solar and geomagnetic activity.	Enhances fundamental understanding of space weather interactions with the ionosphere.	Statistical study only establishes correlation; further work is needed on causation mechanisms.
Gao et al. 2021	3D electromagnetic modeling	Simulations	Successfully simulated induced electric fields from geomagnetic variations in continental-scale models.	A significant advancement in physics-based GIC modeling accuracy and realism.	Requires validation using data collected from the field during actual GMD events.
Beamish et al. 2002	Measurements	UK grid	Measured GICs correlated with geomagnetic fluctuations, establishing an observed relationship.	Helped validate calculations relating geoelectric fields to GIC flows for a real grid.	Only covers a single geographic region and needs extension to other areas.
Liu et al. 2021	Field measurements	China pipelines	Detected electromagnetic interference signals correlated with solar storms.	Rare direct evidence of space weather impacts on pipeline operations.	Limited measurements may not fully capture a range of GIC impacts.
Si et al. 2023	Simulations	Test system	GICs reduced the system's small signal stability, with damping ratios declining over 30%.	Indicates a new mechanism by which GICs could threaten grid stability and needs further study.	Test cases may not fully reflect the complexity of large, interconnected modern grids.

Chen et al. 2023	Sensor system	Prototype device	Developed a geomagnetic sensor with orientation error < 0.5° during tests.	It could significantly improve geomagnetic field monitoring accuracy for GIC applications.	Requires extensive field testing under varying real-world conditions.
Pulkkinen et al. 2010	Modeling	Japan grid	Simulated GICs with a max of around 300 A during storm scenarios. At-risk transformers identified.	Provided risk assessment insights for a national grid to inform mitigation efforts.	Modeling needs validation from GIC measurements on the actual grid.
Kai-Rang et al. 2012	CME data analysis	1998-2011	71% of intense storms were associated with EDA CMEs. EDA CME speeds correlated with storm strength.	Identified specific CME types most associated with severe geomagnetic storms.	Statistical studies cannot definitively establish causality. Many other solar and space factors also contribute to storm intensity.
Hussein and Ali, 2016	Simulations and experiments	Transformer models	Inserting 2-3 ohm ground resistance limited GIC flow, preventing half-cycle saturation.	Proposes a potential mitigation approach to suppress transformer impacts through controlled grounding.	Testing was limited to model transformers at the laboratory scale and needs validation in full-scale field environments.
Wirsing and Mili 2020	GIC measurements analysis	US grid	Multifractal analysis correlated GIC fluctuations with solar wind turbulence.	Provides new techniques to relate GIC statistics to space environment evolution.	A single monitoring location may not capture all spatial characteristics.
Adhikari et al. 2019	GIC measurements	Nepal grid	GICs up to 14.5A were measured, with frequency spreading during storms.	Characterized GIC behavior in Nepal for the first time, establishing the spatial scale of events.	Limited to a single observation station, it lacks multiple points to map regional GICs fully.
Chattopadhyay and Khondekar 2023	CME database	1996-2018	Fast halo CME speeds positively correlated with storm strengths.	It helps identify the most geoeffective CME types to improve forecasting.	Statistical correlations require more physics-based modeling.
Zein et al. 2022	Animal tracking and geomagnetic data	Multiple species	Simulations showed birds could navigate using geomagnetic parameters.	Provided evidence for the controversial magnetic sensing hypothesis in long-distance animal migration.	Many simplifying assumptions are made in simulation models.

Eslamlou et al. 2023	Literature review	60+ articles	Summarized magnetic sensing techniques for NDE of construction materials.	Useful reference covering a range of magnetic NDE applications.	Qualitative assessment only lacks quantitative meta-analysis.
Eroshenko et al. 2010	GIC measurements	Russian railways	Detected GIC peaks up to 30A during storms, causing interference.	Showed that space weather can affect rail signaling systems over large areas.	Measured at only two stations, it lacks complete network coverage.
Carroll et al. 2014	Literature review	100+ articles	Synthesized knowledge on submarine CO2 storage risks.	A valuable reference for an emerging carbon sequestration approach.	Qualitative summary, quantitative analysis lacking.
Despirak et al. 2023	GIC measurements	Russia's grid and pipeline	Measured GICs up to 250A during the 2017 storm.	Provided new GIC data for understudied high-latitude networks.	Limited to a single storm event
Hapgood 2011	Review	N/A	Identified risks of extreme space weather, including GICs, radiation, and radio blackouts.	Highlighted the variety of space weather impacts requiring preparedness.	Qualitative assessment lacks quantitative risk analysis.
Hapgood 2011	Review	N/A	Identified risks of extreme space weather, including GICs, radiation, and radio blackouts.	Highlighted the variety of space weather impacts requiring preparedness.	Qualitative assessment lacks quantitative risk analysis.
Lehtolainen et al. 2022	Instrument characterization	Prototype X-ray detectors	Measured energy resolution <500 eV in the 6-25 keV range. Flux sensitivity 0.6 mCrab.	Demonstrated novel compact X-ray detectors for CubeSat hard X-ray observations.	Requires testing in the actual space environment.
Fry 2015	Policy review	N/A	Assessed space weather risks and national preparedness policies globally.	A valuable reference for space weather policy development.	A qualitative summary and quantitative policy analysis are lacking.

4. Discussion

The preceding sections summarized current knowledge on the causes, impacts, and mitigation approaches for geomagnetically induced currents based on a systematic review of recent technical literature. However, substantial research gaps remain to fully characterize and manage the GIC risk as grid infrastructure evolves and societal dependence on technology increases [32, 33]. This section discusses priority areas for future investigation identified from the review. While first principles of physics-based modeling can now simulate GIC flows in grids based on space weather inputs, improved accuracy and validation are needed for robust predictions, especially at regional scales. Advanced modeling should assimilate real-time geomagnetic and geoelectric field observations to constrain simulations. Detailed subsurface conductivity mapping will reduce uncertainty in the geoelectric field models. High-resolution network models are also required to capture GIC propagation details. International collaboration and data sharing will aid the development of global GIC models [34-36]. Most studies have focused on GIC impacts on conventional AC transmission networks. However, grids evolve with high-voltage DC links, renewable generation, storage, electric vehicles, and distributed energy resources. The vulnerability of these emerging grid technologies requires investigation through modeling, laboratory studies, and field data collection as they are deployed. Special attention should be given to interconnected AC-DC hybrid grids [37, 38].

Expanded GIC, geomagnetic, and geoelectric field monitoring provide invaluable data for analysis, modeling validation, and early warnings. Optimal monitor placement considering cost and coverage is needed. Measurement technology development could enable GIC monitoring on distribution grids. Real-time measurement assimilation into forecasting models will become increasingly viable. Global coordination of ground-based monitoring and satellite systems can provide complete spatial coverage [39-41].

Advancing forecasting capabilities will require an integrated approach combining improved modeling, measurement expansion, and space weather monitoring. Investments in solar imaging and situ solar wind monitoring can extend the lead time for storm predictions.

However, a better understanding of how forecast uncertainties propagate into potential GIC impacts is needed for actionable early warnings to grid operators. Warning criteria should be established based on GIC risk levels rather than storm strength [42-44].

Governing bodies should continue developing engineering standards, planning guidelines, and security rules to enhance GIC resilience. Compliance incentives and public-private partnerships can promote adoption. Regulations for critical infrastructure GIC impact assessments may be warranted. Policy is also needed to support GIC research, monitoring, and international coordination. Outreach and education will raise awareness of GIC threats among stakeholders [45-48].

A holistic understanding of GIC risks from space weather origins to grid impacts requires the interdisciplinary collaboration of space physicists, geophysicists, electrical engineers, network analysts, economists, and policy experts. Constructing this expertise chain will enable the translation of research into practical mitigation strategies. Partnerships between academia, industry, and government organizations should be fostered. Conferences, workshops, and joint projects can catalyze integration [48, 62-66].

So, fully realizing GIC mitigation will require extensive work across the modeling, measurement, prediction, engineering, economic, and policy domains. Increased data sharing and cooperation between nations, academia, and industry will expedite advances. Meeting the GIC challenge is crucial as modern civilization increasingly relies on space-based services and electricity. An intense research agenda lies ahead to maintain the resilience of critical technological infrastructure against this natural hazard arising from the Sun and Earth's magnetic fields [67-69].

5. Future Work

As modern power grids grow in complexity with increasing penetration of renewable generation, storage, electric vehicles, and innovative grid technologies, GIC vulnerability and mitigation strategies for these emerging systems remain an open question. Most studies to date have focused on traditional bulk transmission grids. More research is needed on coordinated forecasting and measurement efforts to improve regional GIC predictability and threat awareness [70, 71]. Global expansion of GIC monitoring networks with data sharing would aid these predictive capabilities. Finally, a critical unresolved need is identifying optimal strategies for hardening grids against GICs, given constraints on time, budgets, and grid stability impacts. Combining engineering and economic modeling, cost-benefit analysis could help prioritize the most critical mitigation upgrades. Addressing these open issues will require multidisciplinary coordination across space science, geophysics, power engineering, economics, and public policy. Significant work remains to translate our scientific understanding of GICs into actionable mitigation strategies as grid infrastructure and threats evolve.

6. Conclusion

This systematic review synthesized recent studies on Geomagnetically Induced Currents (GICs) in power grids. The goal was to survey the current knowledge and gaps to guide future work. The research shows that GICs arise from complex interactions between space weather, Earth's magnetic field, and power grid topology. However, significant questions remain concerning how exactly these factors interrelate. Most concerning is that models poorly predict GIC distribution during storms, limiting mitigation strategies.

Transformer saturation is the most disruptive GIC impact, often causing heating, vibration, and failure. However, effects beyond transformers require attention, like stability issues and reactive power loss. Studies assume transmission grids are most vulnerable, but risks for emerging technologies are unclear. Proposed mitigation strategies show promise but lack a systematic cost-benefit analysis to optimize grid hardening given economic and operational constraints. While hardware solutions like blocking devices, improved forecasting models, and grid topology changes can suppress GICs, their full-scale implementation is gradual. As grid infrastructure modernizes with renewables and storage, its evolving GIC vulnerability remains uncertain. Realizing resilient power grids requires an interdisciplinary research agenda and industry-academia-government coordination. Key knowledge gaps needing attention span space physics, geophysics, power engineering, economics, and public policy domains. Cross-collaborative efforts that transfer insights across these fields can pave the path to managing GIC risk amidst growing grid complexity and space weather uncertainties. Significant challenges remain, but there are also opportunities for progress to secure critical infrastructure against this natural hazard. Even though a conclusion may review the main results or contributions of the paper, do not duplicate the abstract or the introduction. For a conclusion, you might elaborate on the importance of the work or suggest the potential applications and extensions.

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