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The Estimation of the Geomagnetically Induced Current Based on Simulation and Measurement at the Power Network: A Bibliometric Analysis of 42 Years (1979–2021)

KHARISMI BURHANUDIN[1], MOHAMAD HUZAIMY JUSOH[1], (Member, IEEE), ZATUL IFFAH ABDUL LATIFF[1], (Member, IEEE), MOHD HELMY HASHIM[1], AND NUR DALILA KHIRUL ASHAR[2,3], (Member, IEEE)

[1]School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor 40450, Malaysia
[2]Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor 43400, Malaysia
[3]College of Engineering, Universiti Teknologi MARA (UiTM), Cawangan Johor Kampus Pasir, Masai, Pasir Gudang, Johor 81750, Malaysia

Corresponding author: Mohamad Huzaimy Jusoh (huzaimy@uitm.edu.my)

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ABSTRACT GIC (geomagnetic induced current) is a natural current that flows through a conductive substance. The purpose of this study is to provide bibliometric analysis on the computation of the GIC at the Power Network, since determining the backflow current's threshold limit is crucial to avoid electrical equipment failure. The methodology of the study includes topics, scope, and eligibility, as well as screening and an analytical screen paper. From 1979 to 2021, we investigate the evolution of bibliometric studies on the assessment of the GIC at the power network. According to the statistics, there are 601 Scopus articles and 357 Web of Science (WoS) papers in the study on GIC at the power network that focus on estimation from 1979 to 2021. According to the data, the Engineering and Energy disciplines contribute the most to research on predicting the GIC at the Power Network. The words ''geomagnetically induced current,'' ''reactive power,'' and ''geomagnetism'' are commonly used instead of ''magnetic storm,'' ''power grids,'' and ''geoelectric fields.'' The bibliometric method encompasses themes, scope and eligibility, screening, and screen paper for all publications in a search for developing subjects based on Scopus and WoS to map the time-trend, disciplinary distribution, and high-frequency keywords.

INDEX TERMS GIC, bibliometric, scopus, WoS.

I. INTRODUCTION

The interaction between the solar wind and the earth magnetosphere induces a time-varying geomagnetic field on the ground, which flows through ground-based systems such as power grids, pipelines, and railways via the connecting conductive material [1]–[4]. Geomagnetically Induced Current is the current that travels through the conductive substance (GIC). Transformer half-cycle saturation, harmonic distortion, and reactive power loss are all caused by GIC flows in the power network [5]–[9]. GICs have previously caused transformer melting [9] and, in some cases, major power outages, such as the historic breakdown of the Hydro-Québec power system in Canada during the geomagnetic storm of March 13 [2], [10], [11], which left the 6 million citizens of Québec without power for more than 9 hours. In today's world, the cost of a widespread power outage is expected to be in the billions of euros per day for advanced economies [2]. From 1979 to 2021, a huge number of studies on GICs in high-voltage (HV) Power Networks were published Initially, studies on GIC found that the impact of GIC is more dangerous in the polar zone than in the high-latitude region. The GIC study has attracted international attention because of an unknown threshold limit that could pose a threat to the HV power network. The computation of the geoelectric field from magnetic field fluctuation data in combination with an electrical conductivity model of the region [2], [12]–[16] is a key component for estimating the GICs level (1). (2) a correct

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description of the HV transmission system, including network resistances, substation earthing points, and power line paths [2], [17]–[19]. The number of research papers being published is steadily rising. Only a handful of the research topics include concepts, methodologies, applications, and management. As a result, providing a summary of published research is advantageous so that interested researchers can rapidly learn about the study profile thus far. By applying the special search keyword, the bibliometric study was able to examine the academic research output connected to "The Estimation of Geomagnetic Induced Current based on Simulation and Measurement at the Power Network." Scopus' publication index was used to acquire the entire examined publication. The data was collected between 15 July 1979 and 10 November 2021 at 09:15:00 Malaysian Time on 10 November 2021. The search categories are the publication's Title and Abstract keywords, and the results are then given.

II. LITERATURE REVIEW

There are about 601 publications in Scopus and 357 publications in WoS consist of the related study on "The Estimation of Geomagnetic Induced Current based on Simulation and Measurement at the Power Network". The earliest papers on GIC are in 1979 studied the Harmonics and Switching Transient in the presence of Geomagnetic Induced Current publish on 2 February 1981. The GIC recorded from the neutral cable of the three-phase transformer cause half-cycle saturation [20]–[25]. Due to the use of extra-high voltage (EHV) and ultra-high voltage (UHV) lines for electrical transmission, the observed GIC from the neutral point of the transformer surpasses 100 amps. The issue of GIC has become more acute because of the more strongly anchored practice of EHV and UHV [20]. There are various studies on GIC in the 1980s that are related to the high voltage power grids [26]–[34]. The GIC papers in 1980s focus on the GIC effects on the harmonics, switching transient, transformer and relay performance, high voltage direct current (HVDC) converter and transmission system [26]–[34]. In the 1990s the Study on GIC evolved to the simulation on the GIC by using a computer program [35], the design of the blocking/bypass device to prevent the flow of the GIC in Power System [36], neural network application on GIC [37], and Systematic Finite Element Simulation (FEM) on GIC [38].

The study on GIC evolved over time, therefore identifying the cluster of the GIC in the year 2021 is important to understand the current trend of the study on the GIC. From 2000 to 2010, the study on GIC evolve to the calculation of the surface of an electric and magnetic field of geomagnetically induced current from the ground [39], study on the ionospheric current that causes rapid geomagnetic variation which results in strong GIC [40], improved model of the GIC simulation and introduction to the test model for GIC computation algorithm [41]. The study on the GIC in low latitude transmission networks from Brazil is also being investigated majorly based on the geomagnetic disturbance (GMD) data on 7th to 10$^{\text{th}}$ November 2004 [42]. China identifies high GIC from the Power Network based on the study by [43]. There are also study conducted for the Sweden 400kV power grid to analyze the GIC level [44]. From 2010 to 2021, the study on GIC estimation evolved and about 427 publications on the GIC at the Power Network have been traced by using the special keyword.

The investigation of GIC was conducted at both mid and low latitude to determine the GIC's threshold limit. The GIC research from 2010 to 2021 has made significant contributions to the area of study, including assessing the finite element approach for modelling geoelectric fields [45], and evaluating the finite element method for modelling geoelectric fields [46], modelling a 3D earth conductivity structure for GIC computation [47], and investigating severe auroral electrojet indices that result in high GIC [48], Geomagnetic Induced Currents in Power Transformers: Core Saturation Effects [49], Suppressing GIC with Control Ground Resistance on the Transformer [50]. Statistical Relationship between the variation of the Geomagnetic field, Reactive Power Optimization Strategy for Mitigating Voltage Fluctuation in Power Network Caused by Geomagnetic Storm [51], Latitudinal Dependence of Geomagnetically Induced Current during Geomagnetic Storm [52], Reactive Power Optimization Strategy for Mitigating Voltage Fluctuation in Power Network Caused by Geomagnetic Storm [53], predict violent GIC threatening Power Grids using PC indices [54], and Study the Spatial Scale of the Geomagnetic Pc5/Pi3 pulsations as a factor of their efficiency in the generation of Geomagnetically Induced Current [55]. The major contribution of this paper is highlighted as follows:

1) The bibliometric study of "The Estimation of Geomagnetically Induced Current at the Power Network" is examined to better understand the field's recent development and key structure. It will serve as a starting point for scholars interested in working on this under-researched but potentially important topic.
2) Based on the Scopus and WoS indices, the bibliometric analysis examines the growth of research in terms of the number of publications and total citations obtained over time.
3) In addition, the best of 20 entities in the field of "Geomagnetically induced current at the power network" are extracted in terms of authors (productive and influential), discipline, source (productive and influential), countries, institutions (productive and influential), and highly influential papers.
4) The latest and influential works are summarized and explained in depth based on the bibliometric analysis, with a focus on "estimation," "geomagnetically induced current," "power grid," and "power network."
5) The researchers can infer the inner structure and acquire a broad image of the area based on this research

FIGURE 1. Flow diagram of the search strategy.

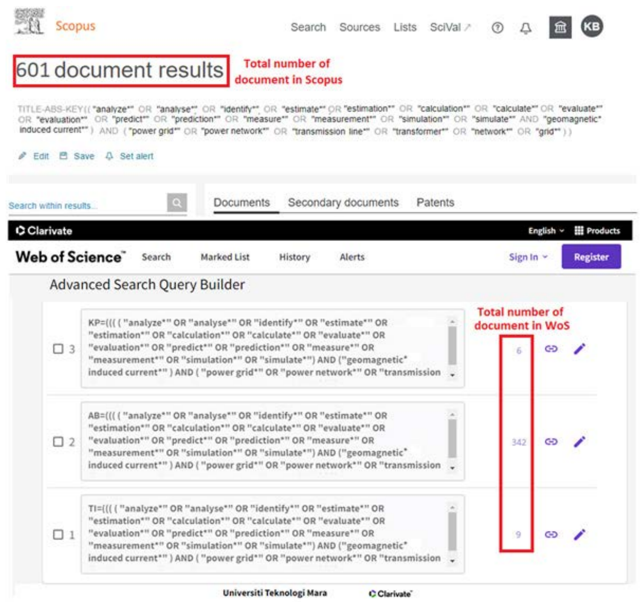

FIGURE 2. The keyword included in the search group of WoS and Scopus.

6) This is a one-of-a-kind study that emphasizes both the bibliometric and detailed review of the Geomagnetically Induced Current in the study.

III. DATA COLLECTION AND METHOD

The data is gathered from the Scopus and Web of Science repositories, which are the two most popular bibliometric databases. Our primary goal is to do a bibliometric analysis of "GIC," hence the keywords included in the search query are as follows: Title-Abstract-Keyword: ("analyze*" OR "analyse*" OR "identify*" OR "estimate*" OR "estimation*" OR "calculation*" OR "calculate*" OR "evaluate*" OR "evaluation*" OR "predict*" OR "prediction*" OR "measure*" OR "measurement*" OR "simulation*" OR "simulate*" AND "geomagnetic* induced current*") AND Title-Abstract-Keyword: ("power grid*" OR "power network*" OR "transmission line*" OR "transformer*" OR "network*" OR "grid*") Timespan: 1979– 2021. The total publication found by searching the following keywords, according to Scopus, is 601. From the 15th to 20th of July 1979, the earliest article based on the search query was titled "Harmonics and Switching Transients in the Presence of Geomagnetically-Induced Currents" authored by [20].

The number of publications indexed by WoS is 357, with the earliest one dating from May 1992 and named "Geomagnetic Effects Modelling for the PJM Interconnection System .2. Geomagnetically Induced Current Study Results" authored by [35]. Author, title, abstract, country, citation record, and author affiliation are among the tags that are retrieved (from WoS and Scopus). In WoS, a total of 357 publications were extracted, with articles (263), reviews (2), conference papers (105), book chapters (2), and notes (2) being the five different document kinds (1). Articles (383), reviews (8), conference papers (196), conference review (4), book chapters (6), book (3), and notes (3) are the eight types of documents found in Scopus (1). Table 1 lists all the different categories of documents. The percentage of contribution of a given document type is represented by 'percent' in this case. The gathered data is analysed using the bibliometric analysis' specific search keyword. We chose Total Papers (TP), which represents the total number of publications from the source, Total Citations (TC), which represents the total number of citations received by the publication, and Citations Per Paper (CPP), which represents the total number of received citations count divided by the total number of publications. The Impact Factor (IF) is a commonly used metric for evaluating journals. It is derived using the average citations of that journal's publications over the previous two or five years. Fig. 1 shows the flow diagram of the search strategy for bibliometric analysis and Fig. 2 shows the keyword included in the search group of Scopus and WoS before being analyse by VOS viewer, Publish and Perish software and readymade bibliometric analysis template.

IV. BIBLIOMETRIC ANALYSIS

This section is divided into sub-sections such as research growth and most productive authors, topmost subject areas, top source referenced, country-by-country analysis,

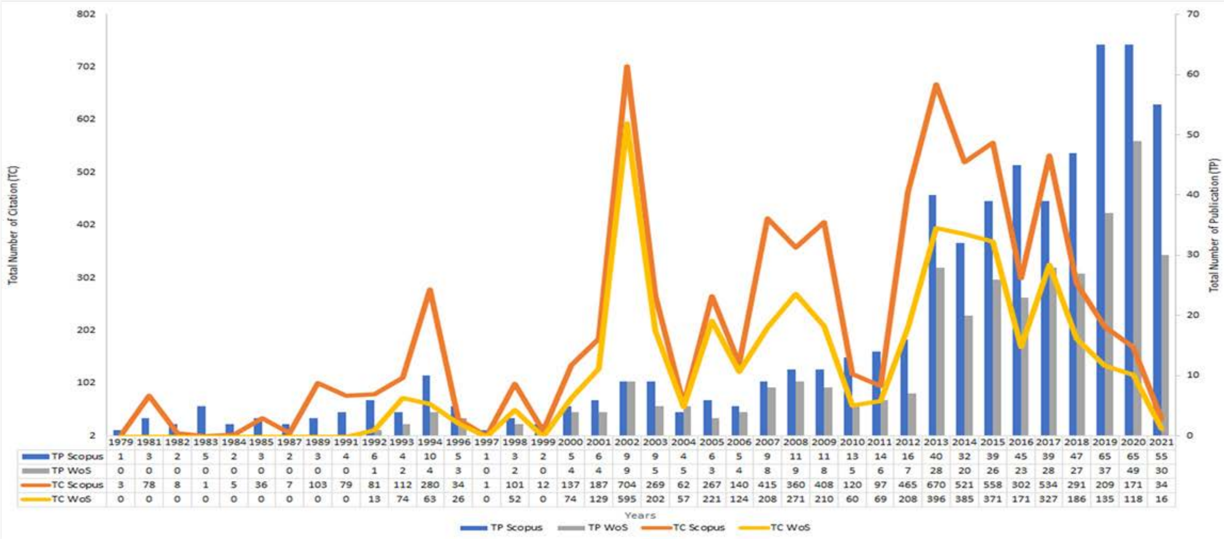

FIGURE 3. Publication growth and total number of citations over the year.

TABLE 1. List of the bibliometric categories of documents.

Document Type	Scopus		WoS	
	Total Publications (TP)	Percentage (%)	Total Publications (TP)	Percentage (%)
Article	383	63.73%	263	70.51%
Conference Paper	196	32.61%	105	28.15%
Review	8	1.33%	2	0.53%
Book Chapter	6	1.00%	2	0.53%
Conference Review	4	0.67%	0	0.00%
Book	3	0.50%	0	0.00%
Report	1	0.16%	1	0.28%
Total	601	100	357	100

institution-by-institution analysis, and highly influential papers in the field of ‘‘estimate geomagnetically induced current’’.

A. RESEARCH GROWTH AND PRODUCTIVE AUTHOR

The field of ‘‘Estimation of Geomagnetically Induced Current in Power Network’’ has gained a reputation in recent years due to its huge significance in various fields. The potential of the study on the Estimation of the GIC at the Power Network is increasing and the major growth started in 2013 and still increasing until the year 2020. In the year 2021, the projection of the whole publication is still not yet known since the acceptance of the publication is still open. Fig. 3 shows the Publication Growth and total number of Citation every year. The first publication indexed by Scopus is from 15 July 1979 and WoS on May 1992. The total number of publications in Scopus is 601 while WoS is 357. The total number of citations recorded in Scopus is 7862 and WoS is 4761. The number of publications and citations increases rapidly in Scopus and WoS since 2013.

There are huge differences in the total number of citations and publications between the years 2012 and 2013. From 2013 onwards, the total number of publications from Scopus and WoS contribute about 71.04% and 75.1% of the overall publication since 1979 for Scopus and 1992 for WoS. Based on Scopus, the highest number of publications could be seen in the years 2019 and 2020 with 65 publications each year. The current total publication from the year 2020 is 55 based on the data collected on 12 November 2021. In WoS, the highest publication year is in 2020 with 45 publications, currently, in 2021 the total recorded publication is 30 and the data was collected on 25 November 2021. In 1994, there are a sudden increase in the number of publications indexed by Scopus and WoS in that year. Scopus recorded having 10 publications while WoS had 4 publications. Then the publication decreases in the following year before increases in the year 2002 and 2003. Overall, the total number of publications shows a significant growth in the research study conducted on the GIC. The total number of citations from Scopus is 7862 and WoS is 4761.

TABLE 2. Top 20 most productive authors.

	Scopus					WoS			
Author's Name	TP	TC	C/CP	*h*	Author's Name	TP	TC	C/CP	*h*
Liu, L.	42	326	8.81	10	Pirjola R	34	916	28.63	18
Pirjola, R.	36	1210	34.57	20	Viljanen A	25	663	28.83	15
Overbye, T.J.	29	458	20.82	10	Liu LG	23	236	16.86	7
Viljanen, A.	27	826	31.77	16	Boteler DH	18	309	19.31	10
Liu, C.	26	179	7.78	8	Overbye TJ	18	173	21.63	3
Liu, L.G.	26	410	19.52	8	Liu CM	16	248	19.08	7
Boteler, D.H.	22	503	22.86	14	Cilliers PJ	14	132	12.00	5
Gaunt, C.T.	17	233	16.64	6	Pulkkinen A	14	495	38.08	11
Rezaei-Zare, A.	16	232	17.85	6	Rezaei-zare A	14	157	15.70	5
Beggan, C.D.	13	271	22.58	9	Thomson AWP	14	363	25.93	10
Dalzell, M.	13	267	22.25	8	Beggan CD	13	262	21.83	9
Pirjola, R.J.	13	297	22.85	9	Gaunt CT	13	146	16.22	4
Pulkkinen, A.	13	638	49.08	13	Rodger CJ	13	179	14.92	8
Thomson, A.W.P.	13	268	20.62	9	Dalzell M	12	171	15.55	7
Marti, L.	12	250	20.83	7	Pirjola RJ	11	203	18.45	7
Rodger, C.J.	12	180	16.36	7	Marti L	10	149	24.83	5
Cilliers, P.J.	10	125	12.5	5	Divett T	8	110	15.71	6
Pilipenko, V.A.	11	42	5.25	4	Pilipenko VA	8	48	6.86	4
Liu, C.M.	10	325	36.11	6	Richardson GS	8	76	9.50	5
Shetye, K.S.	10	148	18.5	4	Boteler D	7	229	32.71	6

The number of citations over the year fluctuated, there is a sudden increase in publication number in a few years both for Scopus and WoS and a sudden drop in the number of publications in certain years. In the year 2001 to 2002, the total citation number for both Scopus and WoS shows the high differences compare to the other years where Scopus from 187 to 704 citations and WoS from 129 to 595 citations. The total number of citations in 2002 become the highest number of a citation for Scopus and WoS where the closest citation number in Scopus is 670 and 396 for WoS in the year 2013. Stating the obvious that growth in this domain is remarkable over the years, the number of citations per paper over the years fluctuates as shown in Fig. 3. From both indexing databases, the most productive writers list is derived and rated based on the total number of papers. Table 2 lists the top ten most productive authors, with a side-by-side comparison of the two databases. According to Scopus, Liu, L. from North China Electric Power University, Beijing, China is the highest contributor with 42 total publications with 326 total citations recorded in this field of "Estimation of the GIC in Power Network". He is followed by Pirjola, R. with 36 publications and astounding 1210 total citations recorded over the published paper. Followed by Overbye, T.J from Texas A&M University published 29 papers with a total of 458 citations.

The publication of each top 20 authors publishes a minimum of 10 publications and contributes 61.89% of total publication on the search keyword field. The lowest ranked from Scopus is Shetye, K.S able to publish 10 publications with 148 total citations. According to WoS, the highest contributor in the search keyword field is Pirjola, R from Finnish Meteorological Institute, Finland with 34 publications and 916 total citations. The number of publications in Scopus is more than WoS due to the high-quality journals list from the WoS, where the Scopus index consists of various sources including conferences. The second most productive author is Viljanen, A. from the same university as Pirjola, R with 25 publications and a total of 663 citations. Followed by Liu, L.G from North China Electric Power University, China with 23 publications and a total of 236 citations. The last in the list was filled by Boteler, D. from Geological Survey, Canada with 7 publications and 229 total citations. Based on WoS, the top 20 authors contribute 82.07% of total publications in the search keyword field. Table 2 shows the list of Most Productive Authors from Scopus and WoS.

B. DISCIPLINE WISE AND TOP JOURNAL SOURCES

The WoS and Scopus repository assigns a subject category to the papers indexed by them. We have extracted the top 17 disciplines with a research study in the field of "The Estimation of Geomagnetic Induced Current based on Simulation and Measurement at the Power Network" which are shown in Table 3. The research areas which contribute the most are from Engineering Field with 369 publications for Scopus and 181 for WoS. For Engineering Field in Scopus, the publication contributes 61.40% of the whole publication

TABLE 3. Top 17 discipline popular in the research topic.

Scopus			WoS		
Subject Area	TP	% of 601	Subject Area	TP	% of 357
Engineering	369	61.40%	Engineering	181	50.7
Energy	245	40.77%	Meteorology Atmospheric Sciences	126	35.294
Earth and Planetary Sciences	197	32.78%	Astronomy Astrophysics	123	34.454
Computer Science	78	12.98%	Geochemistry Geophysics	123	34.454
Physics and Astronomy	60	9.98%	Energy Fuels	47	13.165
Mathematics	45	7.49%	Geology	37	10.364
Materials Science	21	3.49%	Telecommunications	22	6.162
Environmental Science	11	1.83%	Computer Science	21	5.882
Decision Sciences	8	1.33%	Physics	10	2.801
Agricultural and Biological Sciences	3	0.50%	Materials Science	5	1.401
Business, Management and Accounting	3	0.50%	Robotics	5	1.401
Chemical Engineering	3	0.50%	Science Technology Other Topics	4	1.12
Biochemistry, Genetics and Molecular Biology	2	0.33%	Environmental Sciences Ecology	2	0.56
Social Sciences	3	0.50%	Image Science Photographic Technology	2	0.56
Medicine	2	0.33%	Mathematics	2	0.56
Economics, Econometrics and Finance	1	0.17%	Remote Sensing	2	0.56
Nursing	1	0.17%	Automation Control Systems	1	0.28

while in WoS is 50.7%. In Scopus, Energy is becoming the second subject area that contributes 245 publications with 40.77%. It was followed by Earth and Planetary Sciences with 197 publications with 32.78%. The last spot fill by Nursing with 0.17% with 1 publication. The second spot in WoS is Meteorological Atmospheric Sciences with 126 publications and followed by Astronomy Astrophysics with 123 publications at the 3rd position. The last position in WoS is Automation Control System with 1 publication.

There is another subject area that contributes to the research study. Since the research topic is a very vast field, the study on the research field fills the gaps in many subject areas which contribute to publication in various fields. In the academic circle, the journal publication is used to enhance the progress in the related subject area. The new publication will be updated continuously to enhance the knowledge in the field. We have shortlisted the top 20 Journals that are publishing works on ''Estimation of the GIC at the Power Network'' as shown in Table 4. This Sources of the journal are ranked based on the number of publication counts. Based on Scopus and WoS, Space Weather is the best journal for publication on the subject area with 83 total publications for Scopus and 76 for WoS. The list for both Scopus and WoS is similar for until the 5th position which occupied by IEEE transaction on power delivery (Scopus TP = 42, WoS TP = 33), IEEE Power and Energy Society General Meeting (Scopus TP = 23, WoS TP = 18), Journal of Space Weather and Space Climate (Scopus TP = 17, WoS TP = 16) and 'Earth Planets and Space' (Scopus TP = 16, WoS TP = 14). The 6th position in Scopus filled by Dianwhang Jishu Power System Technology with TP = 15 while in WoS filled by IEEE access with TP = 13. At the 20th position in Scopus was filled by Advanced Material Research with 5 publications and WoS filled by AFRICON with 3 publications.

Based on the Total Citation (TC) from the publication, Scopus recorded the highest citation with TC = 1788 while WoS TC = 1590 by Space Weather Journal. The TC for each journal varies depending on the popularity of the Journal. Space Weather Journal seems to be the most productive and popular journal source in the Studied Research Field. In Scopus and WoS, the 2nd highest journal source TC is IEEE transaction on Power Delivery with (TC = 1479) for Scopus and (TC = 802) for WoS. This journal sources are ranked 2nd position in the Top 20 Journal Publishing Work. The 3rd highest TC by Journal Sources is Journal of Atmospheric and Solar-Terrestrial Physics ranked 14 by Scopus with (TC = 452) while in WoS is ranked in 9th position with (TC = 412). The Lowest TC in Scopus is Applied Mechanics and Material Journal Sources with (TC = 2) ranked in 16th and in WoS is IEEE Powering Africa's Sustainable Energy for AD Agenda (AFRICON) with (TC = 0) and ranked 20th. In terms of percentage, All the Journal Sources contributed to the publication evenly. The highest percentage was both filled by Space Weather Journal with Scopus (13.81%) and WoS (21.289%).

C. COUNTRY WISE AND INSTITUTION WISE

We have extracted results based on work distribution over several countries. The related work on ''The Estimation

TABLE 4. Top 20 journal publishing work on the subject area.

Scopus				WoS			
Source Title	TP	TC	% Of 601	Source Title	TP	TC	% Of 357
Space Weather	83	1788	13.81%	Space weather	76	1590	21.289
IEEE Transactions on Power Delivery	42	1479	6.99%	IEEE Transactions on Power Delivery	33	802	9.244
IEEE Power and Energy Society General Meeting	23	92	3.83%	IEEE Power and Energy Society General Meeting	18	22	5.042
Journal Of Space Weather and Space Climate	17	258	2.83%	Journal of space weather and space climate	16	224	4.482
Earth Planets and Space	16	218	2.66%	Earth planets and space	14	213	3.922
Dianwang Jishu Power System Technology	15	124	2.50%	IEEE access	13	28	3.641
IEEE Access	14	37	2.33%	2013 IEEE power and energy society general meeting pes	12	17	3.361
Annales Geophysicae	12	329	2.00%	Annales Geophysicae	10	202	2.801
Electric Power Systems Research	10	83	1.66%	International journal of electrical power energy systems	8	22	2.241
Advances In Space Research	9	222	1.50%	Journal of Atmospheric and Solar Terrestrial Physics	8	412	2.241
IEEE Transactions on Power Systems	9	170	1.50%	Electric Power Systems Research	7	24	1.961
International Journal of Electrical Power and Energy Systems	9	34	1.50%	Journal of Geophysical Research Space Physics	7	178	1.961
Journal Of Geophysical Research Space Physics	8	191	1.33%	North American Power Symposium	7	2	1.961
Journal Of Atmospheric and Solar Terrestrial Physics	7	452	1.16%	Advances in Space Research	6	114	1.681
Proceedings Of the IEEE Power Engineering Society Transmission and Distribution Conference	7	105	1.16%	IEEE Transactions on Power Systems	6	66	1.681
Applied Mechanics and Materials	6	2	1.00%	7th International Symposium on Electromagnetic Compatibility and Electromagnetic Ecology Proceedings	4	25	1.12
Dianli Xitong Zidonghua Automation of Electric Power Systems	6	124	1.00%	Izvestiya Physics of the Solid Earth	4	31	1.12
IEEE Transactions on Power Apparatus and Systems	6	117	1.00%	2017 IEEE power energy society general meeting	3	3	0.84
Zhongguo Dianji Gongcheng Xuebao Proceedings of The Chinese Society of Electrical Engineering	6	85	1.00%	2018 IEEE PES-IAS PowerAfrica Conference	3	2	0.84
Advanced Materials Research	5	4	0.83%	AFRICON	3	0	0.84

of Geomagnetic Induced Current based on Simulation and Measurement at the Power Network'' by several countries is shown in Fig. 4. The top 20 countries are mentioned and ranked based on total publications. According to WoS, around 27.17% of total publications are produced by United States only, with TP of 97. US is followed by Canada (TP=64), China (TP=61), Finland (TP=57) and South Africa in 5th position (TP=31). The highest TC is from Finland on 4th position with (TC = 1416) followed by US (TC = 1352) in 2nd position. In Scopus, around 27.12% of total publications are produced by United States only, with (TP = 163), followed by China (TP=150), Canada (TP=90), Finland (TP=60) and United Kingdom in 5th position (TP=42). The highest TC is from US on 1st position with (TC = 2604) followed by Finland (TC = 1846) in 2nd position.

This section discusses the most productive institution in the World that contribute to the study of the related subject area. The first position in Scopus is filled by North China Electric Power University with total of (TP = 97) and (TC = 928) with overall contribute approximately around 16.14% from total 601 document. In WoS, the 1st rank is fill by Finish Meteorological Institute, Finland with (TP = 55) and (TC = 1405) with overall contribution around 15.41% from total 357 document. The 2nd position in Scopus and WoS is filled by the same institution which ranked 1st, Scopus 2nd position filled by Finish Meteorological Institute, Finland with (TP = 59), (TC = 1838) and contribute around 9.82% overall publication while WoS is filled by North China Electric Power University, China with (TP = 39), (TC = 391) and with 10.92% contribution. The 3rd position in Scopus is filled by University of Cape Town, Africa with (TP = 24) and in WoS is filled by Natural Resources Canada with (TP = 34). The percentage of contribution in Scopus and WoS at 3rd position onwards contribute less than 4% in total publication. The 20th position in Scopus is filled by Catholic University of America with (TP = 9), (TC = 134) and

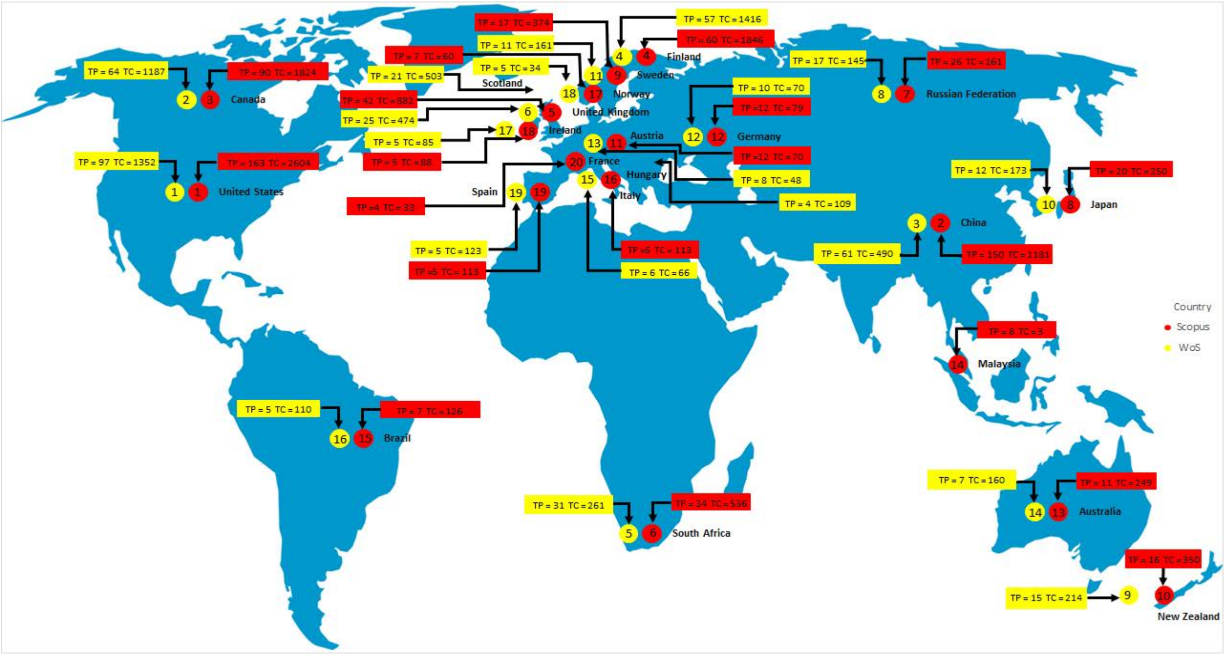

FIGURE 4. Top 20 country contributed to the subject area.

TABLE 5. Top 20 leading institution in publication.

Scopus Institution	TP	TC	% of 601	WoS Affiliations	TP	TC	% of 357
North China Electric Power University	97	928	16.14%	Finnish Meteorological Institute	55	1405	15.406%
Finnish Meteorological Institute	59	1838	9.82%	North China Electric Power University	39	391	10.924%
University of Cape Town	24	292	3.99%	Natural Resources Canada	34	396	9.524%
NASA Goddard Space Flight Centre	21	523	3.49%	Natural Environment Research Council NERC	29	605	8.123%
British Geological Survey	21	433	3.49%	UK Research Innovation UKRI	29	605	8.123%
University of Illinois Urbana-Champaign	19	456	3.16%	NERC British Geological Survey	21	526	5.882%
Geological Survey of Canada	19	471	3.16%	University of cape town	19	167	5.322%
Natural Resources Canada	18	431	3.00%	Nasa Goddard Space Flight Centre	15	380	4.202%
Texas A&M University	17	42	2.83%	National Aeronautics Space Administration NASA	15	380	4.202%
Ontario Hydro Technologies	15	308	2.50%	University of Illinois System	13	170	3.641%
South African National Space Agency	15	106	2.50%	University of Illinois Urbana Champaign	13	170	3.641%
Hydro-Quebec	13	447	2.16%	University of Otago	13	179	3.641%
Transpower New Zealand Limited	13	267	2.16%	Hydro one limited	12	177	3.361%
University of Otago	12	180	2.00%	Russian academy of sciences	12	121	3.361%
Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences	11	30	1.83%	Transpower New Zealand Ltd	12	171	3.361%
Technische Universitat Graz	10	60	1.66%	Texas A&M University College Station	11	25	3.081%
British Antarctic Survey	10	143	1.66%	Texas A&M University System	11	25	3.081%
Geophysical Center of the Russian Academy of Sciences	10	35	1.66%	NERC British Antarctic Survey	10	124	2.801%
Xi'an Jiao tong University	9	1	1.50%	Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences	9	39	2.521%
Catholic University of America	9	134	1.50%	Geophysical Centre of the Russian Academy of Sciences	8	43	2.241%

contribute around 1.5% while in WoS is filled by Geophysical Center of the Russian Academy of Sciences with (TP = 8), (TC = 43) and contribute around 2.24% of total publication.

Based on the Tabulated data in Table 5, the only Asian country in the list is China which is located between Mid and Low latitude region, and South Africa is the country from Africa which is also located between Mid and Low latitude region. The rest of the country are from Austria (Only in Scopus), Canada, Finland, New Zealand, Russia, United Kingdom, and United States. The most popular Institution in the Field of the study is from Finnish Meteorological Institute, Finland which contribute (TC = 1838) in Scopus and (TC = 1405) in WoS. Based on the research study, Table 5 compile Top 20 leading Institution in Publication.

D. TOP 20 HIGHLY INFLUENCE PAPER

The Top 20 Highly influential papers based on the Subject Area are ranked based on the Citation number of the paper. The paper which highly cited based on Scopus and WoS is from Leonard Bolduc titled "GIC observations and studies in the Hydro-Québec power system" in 2002 with (TC = 249) with citation productivity of 13.16 per year for Scopus and (TC = 223) with citation productivity of 11.15 per year for WoS. The 2nd position both in Scopus and WoS is filled by Philip R. Price, Member, IEEE paper title "Geomagnetically induced current effects on transformers" with (TC = 166) and 8.74 ratio of citation per year in Scopus. In WoS, the (TC = 103) and ratio of citation per year is 5.15. The 3rd position in Scopus and WoS is filled by the same paper authored by Randy Horton, Senior Member, IEEE, etc. with paper titled "A Test Case for the Calculation of Geomagnetically Induced Currents", in Scopus (TC = 136) with ratio citation per year equal to 15.11 while in WoS (TC = 101) with ratio citation per year equal to 10.1. The only book existed in the list is j & p transformer book (2007) indexed by Scopus with (TC = 129) and citation ratio of 9.71 per year, the rest of the Top 20 list is of Journal types.

The last position of highly influential paper in Scopus is filled by the paper authored by J.G. Kappenman; S.R. Norr; G.A. Sweezy with paper titled "GIC mitigation: a neutral blocking/bypass device to prevent the flow of GIC in power systems" in 1991 with (TC = 72) and ratio of citation of 2.4 per year while in WoS last position is filled by the paper authored by Torta, JM; Serrano, L; Regue, JR titled "Geomagnetically induced currents in a power grid of north-eastern Spain" in 2012 with (TC = 53) and total citation of 5.3 per year. Table 6 and 7 listed the Top 20 influential paper in Publication in Scopus and WoS.

E. BIBLIOGRAPHIC LANDSCAPE

In this section, we visualize the bibliographic connection cluster between the top authors in the research field and the field of the study which the authors involved. The simulation is conducted by using VOS viewer which is a platform used to simulate the literature study [56]. It's a tool for visualizing a network of publications, authors, institutions, subject areas, and countries, among other things. The number of times two entities (either writers or countries) cite the same entity is known as bibliographic coupling. It specifies the node-to-node disciplinary connections. Fig. 5 and Fig. 6 visualize the bibliometric cluster according to WoS and Scopus. There are nodes (shown as authors) and links between the nodes in the diagrams. The overlap between the common references in the papers as indexed by the respective repository is represented by the breadth of these links. In Network Visualization (NW) modes, Nodes are also distinguished by their color.

A cluster of comparable elements is formed by nodes of the same color. A cluster is a collection of elements that form a logical unit. The more authors in a cluster, the more co-cited work and linked study topic there is. In Overlay Visualization (OV) mode, the colors indicate the duration of the publication in the Network. The deep blue indicates the papers is the earliest publication on the subject area and bright yellow indicates the new publication in the field. Fig. 5 and Fig. 6 visualized the Scopus and WoS author coupling based on Network Visualization (NV) and Overlay Visualization (OV). In Fig. 5, we can observe 14 different clusters with different colors. The cluster with red color is the biggest with total 15 Authors has Top 20 productive authors such as Boteler, D., Martin, L., Pirjola, R.J. and Rezaei-zare, A. Boteler, D. have been ranked 7th in Scopus and 4th in WoS based on the top 20 most productive authors. The 2nd biggest cluster is from the dark green cluster with total 14 authors and not one of the authors listed in Top 20 most productive authors. When viewing Fig. 5 from Overlay Visualization (OV), we can see that the publication in this cluster is the earliest cluster existed in the subject area based on Scopus. The Cluster which studies the latest publication in the area is from cluster 3, 4, 5, 7, and 10 existing 4 Top 20 most productive authors which is Beggan, C.D., Dalzell, M., Divett, T., and Richardson G.S. The publication dates back from 2017 onwards. In Fig. 6, There are total of 8 cluster with different colors. The biggest cluster is the red color cluster with total of 12 authors with Pirjola, R. and Viljanen, A as the Top 20 most productive authors, both are ranked 1st and 2nd in WoS.

The 2nd biggest cluster is from the dark green cluster with total of 9 authors with Pulkkinen, A as the Top 20 Most productive authors. When viewing Fig. 6 from the OV, we can see the visualization of the publication date from old to the latest publication cluster. Based on the OV visualization, the latest publication coming from cluster 3, 7 and 8 with 4 Top 20 Most productive authors from WoS which is Beggan, C.D, T, Divett, Richardson, G.S, and Roger, C.J. The publication dates back from early 2018 onwards. Fig. 7 and 8 shows the bibliometric coupling of the contributing countries/territories publishing the work from Scopus and WoS with the NW and OV view. Fig 7 shows the Scopus Country Cluster based on the search subject area. There are 10 cluster between the country and the biggest cluster is represented by the red cluster on NW view. This cluster consist of Belgium, Czech Republic, France, Germany, Ireland, Poland, Spain, and United Kingdom. This Cluster consist of publication from 2014 to 2018. The 2nd Cluster is represented by the dark green cluster with total of 5 country Canada, China, Iran, Singapore, and Sudan. The 2nd cluster consist of publication since 1985 until 2020. Finland

TABLE 6. Top 20 influential publication in Scopus.

No.	Authors	Title	Year	Cites	Cites per Year
1	Leonard Bolduc	GIC observations and studies in the Hydro-Québec power system	2002	249	13.16
2	Philip R. Price, Member, IEEE	Geomagnetically induced current effects on transformers	2002	166	8.74
3	Randy Horton, Senior Member, IEEE, David Boteler, Senior Member, IEEE, Thomas J. Overbye, Fellow, IEEE,	A Test Case for the Calculation of Geomagnetically Induced Currents	2012	136	15.11
4	C. T Gaunt, G. Coetzee	Transformer failures in regions incorrectly considered to have low GIC-risk	2007	130	9.43
5	Martin J. Heathcote	j & p transformer book	2007	129	9.71
6	A. P. Sakis Meliopoulos, Fan Zhang, Shalom Zelingher	Power system harmonic state estimation	1994	124	4.63
7	Risto pirjola	Review on the calculation of surface electric and magnetic fields and of geomagnetically induced currents in ground-based technological systems	2002	114	6
8	Chun-Ming Liu, Lian-Guang Liu, and Risto Pirjola	Geomagnetically Induced Currents in the High-Voltage Power Grid in China	2009	108	9
9	John G. Kappenman	An overview of the impulsive geomagnetic field disturbances and power grid impacts associated with the violent Sun-Earth connection events of 29–31 October 2003 and a comparative evaluation with other contemporary storms	2005	104	6.5
10	Thomas J. Overbye, Trevor R. Hutchins, Komal Shetye, Jamie Weber, Scott Dahman	Integration of geomagnetic disturbance modeling into the power flow: A methodology for large-scale system studies	2012	96	10.67
11	Antti Pulkkinen,Olaf Amm,Ari Viljanen	Ionospheric equivalent current distributions determined with the method of spherical elementary current systems	2003	93	5.17
12	M. Wik,A. Viljanen,R. Pirjola,A. Pulkkinen,P. Wintoft,H. Lundstedt	Calculation of Geomagnetically Induced Currents in the 400 kV power grid in southern Sweden	2008	85	6.54
13	Xuzhu Dong, Yilu Liu, John G. Kappenman	Comparative Analysis of Exciting Current Harmonics and Reactive Power Consumption from GIC Saturated Transformers	2001	84	4.25
14	R. A. Marshall, M. Dalzell, C. L. Waters, P. Goldthorpe, E. A. Smith	Geomagnetically Induced Currents in the New Zealand Power Network	2012	78	8.67
15	M. Wik1,2, R. Pirjola3, H. Lundstedt1, A. Viljanen3, P. Wintoft1, and A. Pulkkinen4,5	Space weather events in July 1982 and October 2003 and the effects of geomagnetically induced currents on Swedish technical systems	2009	77	6.42
16	I. Arslan Erinmez, John G. Kappenman , William A. Radasky	Management of the geomagnetically induced current risks on the national grid company's electric power transmission system	2002	76	4
17	S. Watari,M. Kunitake,K. Kitamura,T. Hori,T. Kikuchi,K. Shiokawa,N. Nishitani,R. Kataoka,Y. Kamide,T. Aso,Y. Watanabe,Y. Tsuneta	Measurements of geomagnetically induced current in a power grid in Hokkaido, Japan	2009	74	6.25
18	Chun-Ming Liu,1 Lian-Guang Liu,1 Risto Pirjola,2 and Ze-Zhong Wang1	Calculation of geomagnetically induced currents in mid- to low-latitude power grids based on the plane wave method: A preliminary case study	2009	74	6.17
19	Liu lian-guang, Liu Chun-Ming, ZHANG Bing, WANG Ze-Zhong, XIAO Xiang-Ning, HAN Li-Zhang	Strong magnetic storm's influence on china's guangdong power grid	2008	73	5.62
20	J.G. Kappenman; S.R. Norr; G.A. Sweezy; D.L. Carlson; V.D. Albertson; J.E. Harder; B.L. Damsky	GIC mitigation: a neutral blocking/bypass device to prevent the flow of GIC in power systems	1991	72	2.4

and United States are in cluster 9 and 7 respectively, both country is ranked 1st and 4th in the top 20 most productive country in the search subject area.

Based on the OV view, the latest contribution since 2018 onwards on the study is from Chile (TP = 1), Czech (TP = 3), France (TP = 4), Germany (TP = 12), Iran (TP = 4), Ireland (TP = 5), Italy (TP = 7), Malaysia (TP = 8), Sudan (TP = 1), and United Arab Emirates (TP = 1) with TC = 314. Fig 8 shows the WoS Country Cluster based on the search subject area. There are 7 cluster between the country and the biggest cluster is represented by the red cluster on NW view. This cluster consist of Australia,

TABLE 7. Top 20 influential publication in WoS.

No.	Authors	WoS Title	Year	Cites	Cites per Year
1	Bolduc, L	GIC observations and studies in the Hydro-Quebec power system	2002	223	11.15
2	Price, PR	Geomagnetically induced current effects on transformer's	2002	103	5.15
3	Horton, R; Boteler, D; Overbye, TJ; Pirjola, R and Dugan, RC	A Test Case for the Calculation of the Geomagnetically Induced Current	2012	101	10.1
4	Pirjola, R	Review on the calculation of surface electric and magnetic fields and of geomagnetically induced currents in ground-based technological systems	2002	95	4.75
5	Pulkkinen, A; Amm, O; Viljanen, A; Korja, T; Hjelt, SE; Kaikkonen, P and Lahti,	Ionospheric equivalent current distributions determined with the method of spherical elementary current systems	2003	91	4.79
6	Kappenman, JG	An Overview of the Impulsive Geomagnetic Field Disturbance and Power Grid impacts Associated with the violent sun-earth connection events of 29-31October and a comparative evaluation with other contemporary storms	2005	86	5.06
7	Thomson, AWP (Thomson, AWP) McKay, AJ (McKay, AJ) Clarke, E (Clarke, E) Reay, SJ (Reay, SJ)	Surface electric fields and geomagnetically induced currents in the Scottish Power grid during the 30 October 2003 geomagnetic storm	2005	81	4.76
8	Gaunt, CT and Coetzee, G	Transformer failures in regions incorrectly considered to have low GIC-risk	2007	80	5.33
9	Erinmez, IA; Kappenman, JG and Radasky, WA	Management of the geomagnetically induced current risks on the national grid company's electric power transmission system	2002	71	3.55
10	Watari, S; Kunitake, M; Kitamura, K; Hori, T; Kikuchi, T and Shiokawa, K	Measurements of geomagnetically induced current in a power grid in Hokkaido, Japan	2009	55	5.08
11	Wik, M; Viljanen, A; Pirjola, R; Pulkkinen, A; Wintoft, P and Lundstedt, H	Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden	2008	64	4.57
12	Beggan, CD; Beamish, D; Richards, A; Kelly, GS and Thomson, AWP	Prediction of extreme geomagnetically induced currents in the UK high-voltage network	2013	61	6.78
13	Trivedi, NB; Vitorello, I; Kabata, W; Dutra, SLG; Padilha, AL; Bologna, MS; de Padua, MB; Soares, AP	Geomagnetically induced currents in an electric power transmission system at low latitudes in Brazil: A case study	2007	61	4.07
14	Liu, CM; Liu, LG; Pirjola, R; Wang, ZZ	Calculation of geomagnetically induced currents in mid- to low-latitude power grids based on the plane wave method: A preliminary case study	2009	59	4.54
15	Liu, CM; Liu, LG and Pirjola, R	Geomagnetically Induced Currents in the High-Voltage Power Grid in China	2009	58	4.46
16	Kappenman, JG	Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events - An analysis of observational evidence including the great storm of May 1921	2006	57	3.56
17	Ngwira, CM; Pulkkinen, A; Wilder, FD; Crowley, G	Extended study of extreme geoelectric field event scenarios for geomagnetically induced current applications	2013	56	6.22
18	Boteler, DH and Pirjola, RJ	Modeling geomagnetically induced currents	2017	54	10.8
19	Pirjola, R	Effects of space weather on high-latitude ground systems	2005	54	3.18
20	Torta, JM; Serrano, L; Regue, JR; Sanchez, AM; Roldan, E	Geomagnetically induced currents in a power grid of north-eastern Spain	2012	53	5.3

England, Ireland, Japan, New Zealand, and Scotland. The publications in this Cluster date from 2013 to 2018. The dark green cluster is the second cluster, which includes six countries: Belgium, Czech Republic, France, Germany, Poland, and Spain. The second cluster includes publications from 2013 to 2019. The United States and Finland are in clusters 3 and 4, respectively, and are placed first and fourth in WoS top 20 most productive countries in the search subject area. According to the OV perspective, Chile (TP = 1), Czech Republic (TP = 2), France (TP = 3), Iran

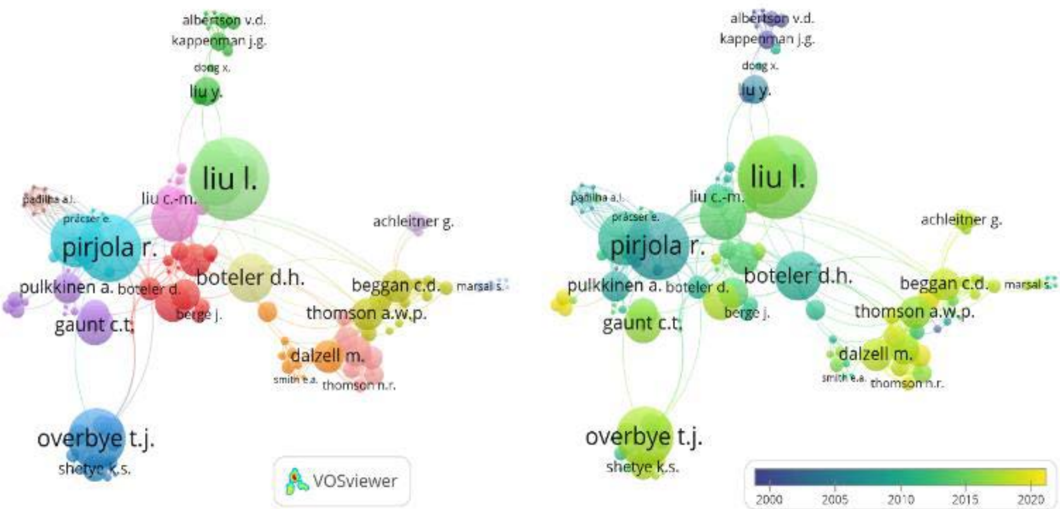

FIGURE 5. Scopus authors coupling (min Document 1, min Citation 50) NW and OV view with 130 Document.

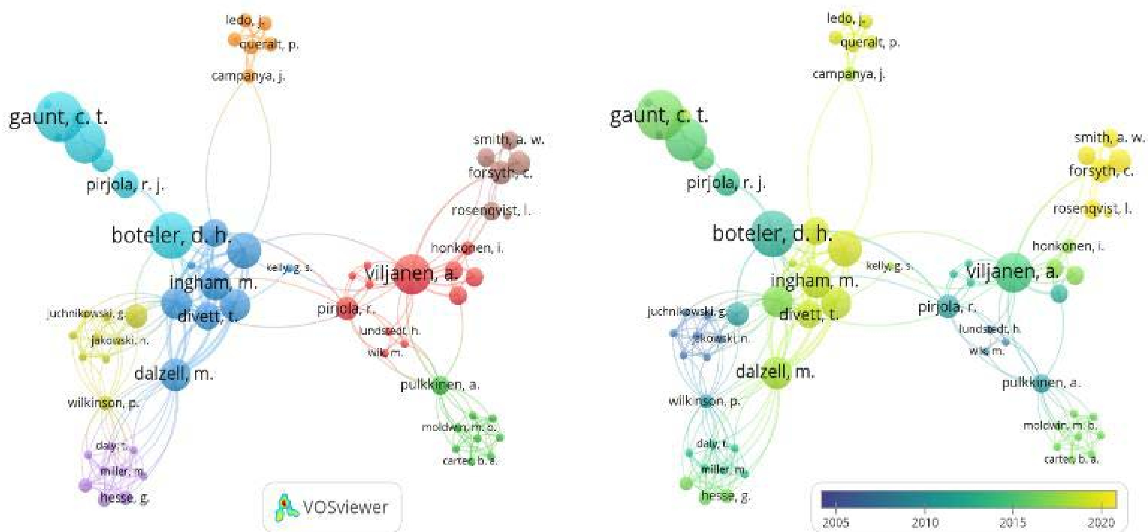

FIGURE 6. WoS authors coupling (min Document 1, min Citation 15) NW and OV view with 68 document.

(TP = 3), Ireland (TP = 5), Italy (TP = 8), New Zealand (TP = 7), Norway (TP = 7) and United Arab Emirates (TP = 4) have made the most recent contributions to the study since 2018.

V. DISCUSSION OF THE RESEARCH WORK ON THE SUBJECT AREA

In this section, we utilized VOS viewer to visualize the most common keywords and analyze what authors hoped to achieve in the most significant articles on the topic of "The Estimation of the GIC based on Simulation and Measurement in Power Network." This section also provides the reader with the rationale that has been used to address big data challenges in recent times, as well as potential areas to research in the future, thereby providing a clearer and better perspective for future studies.

A. KEYWORD SUMMARY ON GEOMAGNETIC INDUCED CURRENT AND GEOMAGNETIC DISTURBANCE

The effect of the Geomagnetic Disturbance on the formation of the GIC is due to the solar storm or a high-altitude nuclear detonation [57]. There are numbers of research conducted to mitigate the level of the GIC throughout the world. In power grid, the level of the GIC is important in evaluating the effects of geomagnetic storm [58]. The earliest study related to geomagnetic disturbance believe that its only threaten the technological system that are elongated in latitudinal (W-E) direction [1], [59]. Some studies show that the impact from geomagnetic disturbance existed considerably lower in variability to its derivative elongated meridionally [59]. The impact from geomagnetic disturbance to the formation of the GIC is higher in high latitude region due to the more prominent geomagnetic activity [60]–[64]. The impact of

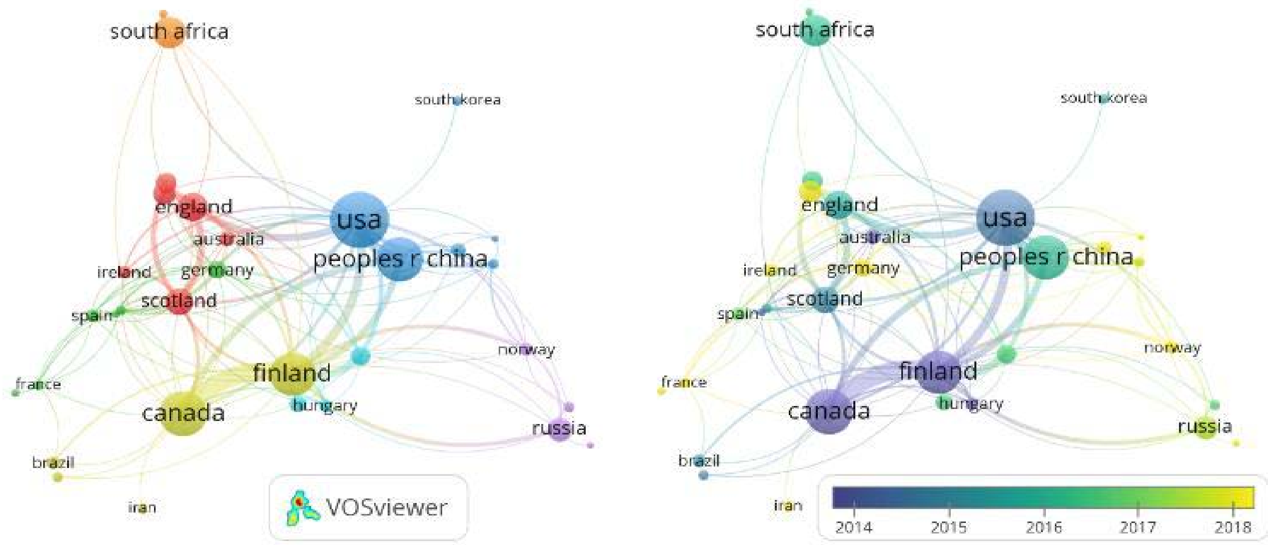

FIGURE 7. WoS country coupling (min Document 1, min Citation 1) NW and OV view with 36 document.

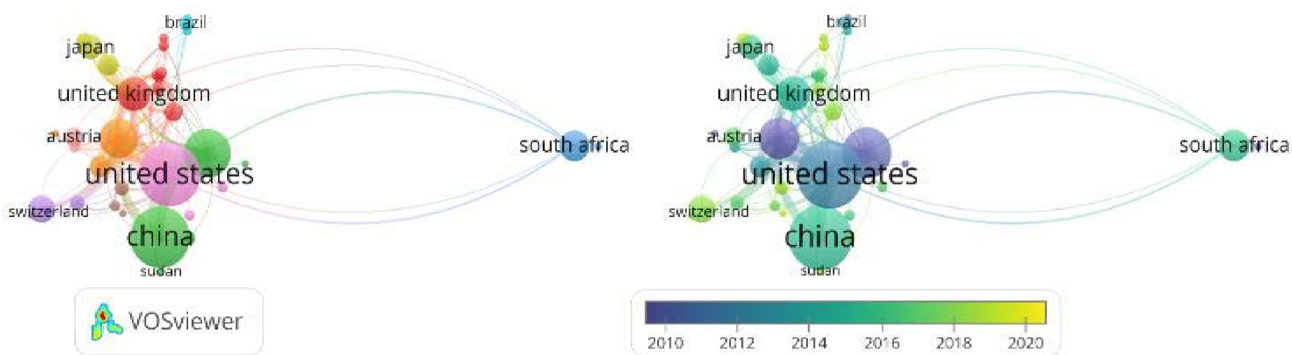

FIGURE 8. Scopus country coupling (min Document 1, min Citation 1) NW and OV view with 45 document.

geomagnetic activity on GIC in the medium and low latitudes was still present, but not as severe as in the high latitudes.

The paper by Forbes and St. Cyr [65] from Canada shows that the potential disruption on the electricity flows between Ontario, Canada and New York State, USA by using simulated model. The model is simulated using hourly data from the geomagnetic field activity on 1st May 2002 through 31 October 2003 and evaluated by using the hourly data from 1 November 2003 to 9 December 2003. In Sweden, study conducted by Rosenqvist and Hall [60] conducted the study on the 3D lateral conductivity map with surrounding ocean to model the geoelectric ground response due to the magnetic field. This process provides higher accuracy on the estimation of the GIC instead of the 1D lateral conductivity map. Klauber *et al.* [8] published a paper on the importance of GIC estimation during magnetic disturbances, stating that GIC estimation during magnetic disturbances is a critical aspect of real-time monitoring and management for power grid operations and control. Situational awareness is provided during GMD incidents because to increased interest in the consequences of GIC and effective mitigation techniques. According to Papers by Zhang and Liu [66], geomagnetic storm disasters have a substantial impact on the electrical system's safe and stable functioning.

Serious geomagnetic storm disasters can result in a chain reaction of power system failures, including voltage breakdown. As a result, it's critical to assess and assess the operating risks of power systems during magnetic storms. Based on the paper by Wang *et al.* [67], the author approach the study by applying the machine learning to detect the GIC in the power grids. The author examining the measured currents from the current transformer (CTs) to detect GIC by using hybrid time-frequency analysis combined with machine learning technology. Based on the paper by Haddadi *et al.* [68], the author studied the test case for geomagnetic disturbances and establish the validation work based on the software simulation to establish the model for GMD benchmark.

Based on the review journal paper on the GIC from [69] the important aspect in modelling the threats to technological systems from space weather is understanding the behavior and chain consequences of this event. This study provides a detailed overview of space weather, geomagnetic disturbances (GMDs), and geomagnetic interference (GICs), as well as their effects on power systems in both high and mid-low latitude locations. The research study conducted by Zhang and Liu [70] developed GIC benchmark model to calculate GIC from East-China 1000kV ultra-high voltage (UHV) and 500kV extra-high voltage (EHV) power grids under a uniform geoelectric-filed of 1V/km. The study found that the characteristics and pattern of the GIC in UHV power grid and identify the high-risk nodes which can be vulnerable to GIC encroachment. The first GIC measurement for 400kV Mexican Power Grid was made in a paper by Caraballo *et al.* [71]. The study discovered that in the event of a Carrington-like event, GIC ranging from 25 to 150 Amp might impact the power system under a homogenous 1V/km east-west geoelectric field.

According to a study by Švanda *et al.* [72] on the immediate and delayed response of the electrical power grid to geomagnetic storms, there is a 5–10 percent increase in the recorded anomalies in the Czech power grid in the 5-day period following the start of geomagnetic activity, and this fraction of anomalies is most likely related to GIC exposure. The author did a measurement and simulation on the GIC based on the Chinese low-latitude substation during geomagnetic storms based on a study by Zhang *et al.* [3], The results show that the physical-based model is better suitable to the prediction of GICs at low-latitude power networks during storms than the persistence model. Study by Zhang *et al.* [73] on the Kalman filter approach on the model and method of calculating and analyzing GIC disturbance using reactive power measured by wide area measurement systems (WAMS) shows that reactive power measured by phasor measurement units (PMUs) can be effectively used to calculate and analyze GIC-Q in transformers, which is important to prevent power grid disasters caused by magnetic storms through dispatch and operation. The study by Nazir *et al.* [57] examines the state of the art in GIC mitigation and elimination strategies, as well as their limitations, and introduces converter-based strategies as a new avenue of power system protection against GICs by presenting novel strategies that involve integrating the proposed schemes between the neutral and ground of power transformers. According to a study conducted by Behdani *et al.* [74] on the investigation of the power transformer ferro resonance phenomenon caused by GICs in series capacitor compensated networks, GICs can significantly increase the vulnerability of power transformers to the occurrence of ferro resonance phenomena. According to a study by Yang *et al.* [75] on static voltage stability during geomagnetic storms, using a 1V/km generated geoelectric field significantly reduces static voltage stability, posing a serious threat to the power system.

B. KEYWORD SUMMARY ON REACTIVE POWER

When Reactive power is the situation where the power that flow back from a destination toward the grid in an alternating current scenario. Study conducted by Piccinelli and Krausmann [76] that analyzed the behavioral of the Power System operational mode during geomagnetic storm found that the geomagnetic storm change the topology of the system, varying path of geomagnetically induced currents and inducing a local imbalance in the voltage stability superimposed on the grid operational flow. Transformer saturation will increase reactive power and cause imbalance and voltage instability for the entire system. Few episodes of instability were found in correspondence with existing voltage instability due to the underlying system load. Based on the study conducted by Halbedl *et al.* [10] on the noise problem in some transformers in Austria. The study found that high geomagnetic disturbance led to high currents according to the simulation and confirm by the measurement data. This current can drive transformers or instrument transformers into half-cycle saturation which lead to higher no-load current, and the reactive power consumption raise.

According to a study conducted by Joo *et al.* [77] on the influence of geomagnetic disturbances on Korean electric power systems, their system maintains voltage stability and increases reactive power throughout the impact of the geomagnetic storm. The Korean electric power system meets all applicable US standards and ensures system stability. According to a study conducted by Stork and Mayer [78] on geomagnetism, magnetic storms, and methods of estimating geomagnetic induced currents on power transformers, the transformer's reactive power increases when it is running in semi saturation mode. The increase in Joule losses in the winding, the iron of the transformers, and the transformer tank occurs when higher harmonics become more prevalent. High-altitude electromagnetic pulses (HEMPs) are bursts of electromagnetic radiation in transmission lines, according to a study done by Jeong [79] The geomagnetically-induced currents and increase in the reactive power absorption of the transformer in the power system were calculated using the Direct Current (DC) equivalent model of Korean power systems. The impacts of detonations at five target locations were compared in the study. It was determined that when affected by an E3 HEMP, Korean electric power systems are unable to maintain their stability.

The study conducted by Zawawi *et al.* [7] on the impact of GIC on selected 275kV sub power system network in Malaysia find out that the value of 315.10 Ω neutral earthing resistor can be used to limit the GIC current flow and thus provide protection to the power system network. Bejmert *et al.* [80] conducted a study on GIC on difficulties originating from DC excitation of power transformers due to geomagnetically induced currents (GIC). This study tallied the number of times the transformer differential protection tripped and proposed two GIC detection algorithms capable of providing adequate transformer differential protection blocking. Based on Zawawi *et al.* [81] work on GIC modelling on the impacts of a GIC on a three-phase power transformer that includes half cycle saturation and reactive power consumption. The magnitude flux and magnetizing current of the power transformer, as well as reactive power consumption, rise because of the simulation results under GIC conditions, potentially leading to power system instability.

C. KEYWORD SUMMARY ON POWER TRANSFORMER AND HARMONIC ANALYSIS

The formation of the GIC usually associated with power transformer due to connectivity existed between the earth surface and the neutral cable of the transformer. Based on the study conducted by Behdani *et al.* [74] on the investigation of the power transformer ferro resonance phenomenon caused by GICs in series capacitor compensated networks, GICs can significantly increase the vulnerability of power transformers to the occurrence of ferro resonance phenomena. Ferro resonant waveforms, which are extremely distorted and heavily laden with harmonic content, can result in poor power quality and possibly protection system failure. Odd and even harmonics are present in significant levels and interact with fundamental-frequency voltage and current components, according to a study by Haddadi *et al.* [82] on test case for geomagnetic disturbances and establish the validation work based on software simulation to establish the model for GMD benchmark.

According to a study by Nazir *et al.* [57], an AC offset that drives power transformers into saturation can result in a substantial draw of reactive power, increased noise level, damage to shunt capacitors and harmonic filters, and improper operation of power system protective equipment. From Heyns *et al.* [83] states that recently risk analysis has been formalized with North American Electric Reliability Corporation (NERC), in compliance with Federal Energy Regulatory Commission (FERC) regarding geomagnetic disturbance reliability standard that associated with GIC risk which cause damage to transformers, with a lesser emphasis on control system disruptions and harmonic production. GIC may generate increased noise emissions, thermal heating spots in transformer's iron due to eddy currents, more harmonic emissions, and voltage disturbances, according to a study by Halbedl *et al.* [10] on the noise problem in some transformers in Austria. As these DC currents (quasi-dc currents for GIC) flow through transformer windings, a series of reactions such as increased harmonic, temperature of oil, vibration, and noise would occur connected with the half cycle saturation of the transformer core, according to a study by H. Lu *et al.* [84]. The DC flowing in the transformer wind can bias the transformer core and produce half-cycle saturation, causing the magnetizing current to distort significantly, resulting in a sudden increase in the harmonics of the magnetizing current. Electrical measurements of voltages, currents, harmonics, and reactive power, as well as the search coil outputs, were recorded in a study by Chisepo *et al.* [85] on part cycle, half wave saturation of a power transformers core produced by leaky DC or Geomagnetically Induced Current. The flux distribution in and around the core was determined using the search coil measurements.

According to a study on GIC and harmonic distortion in single phase bank transformers in substations by Clilverd *et al.* [86], very low frequency (VLF) wideband measuring equipment detects the presence of power system harmonics and high-voltage harmonic distortion. Within 25 hours, two solar wind shocks occurred, resulting in four different GIC episodes. Two GIC events were linked to the occurrence of the shocks itself. There was no visible harmonic production because of these significant but short-lived GIC impacts. The third (150 Hz) harmonic is prominent in the neutral current of the power network, according to a study by Zirka *et al.* [87] on the capabilities of a topological model of a three-phase, five-limb transformer to accurately describe its response when subjected to geomagnetically induced currents. Because the current returning to the distant generator in the back-to-back configuration is equal to the total of currents in the neutrals of the two transformers, this is the case. Harmonic currents may cause relay mis operation and accidental disconnection of reactive power sources such as static VAR compensators, according to a study by Kazerooni & Overbye [88] on line switching as a remedial action to safeguard transformers from geomagnetic disturbances (GMDs).

According to a study conducted by Yang *et al.* [89] on the physical performance of half-cycle saturation and technical solutions to inrush like half-cycle saturated currents, the resulting half-cycle saturated inrush-like current poses significant threats to the safety and economic operation of the entire ac power system, including transformer vibrations, audible noise, hotspot in transformer, excessive reactive power loss, harmonics, and increased thermal and mechanical loads. Study by Wang *et al.* [67] on using machine learning to detect GIC in power grids, the harmonic components generated by GICs act in a variety of ways, and present detection systems do not take into account such complicated interference.

Based on the study by Haddadi *et al.* [68] on the test case for geomagnetic disturbances and the validation work based on software simulation to establish the model for GMD benchmark, large GICs can cause prolonged uni-directional saturation of transformers, which generates harmonics and increases transformer var consumption. Protective relays may unintentionally trip needed equipment due to harmonic currents. Based on the study by Abda *et al.* [69], the exposure to voltage unbalances and harmonics caused by half-cycle saturation in the primary circuit if there is GIC presence in the secondary wye circuit is caused by half-cycle saturation in the primary circuit if there is GIC presence in the secondary wye circuit. In the rotor's end rings, positive sequence harmonics may create mechanical vibrations, and even the harmonics themselves may generate excessive heating [6], [50], [90]–[94]. Generator protection relays, such as traditional negative-sequence relays, are designed to respond to a fundamental frequency imbalance. They may work incorrectly or not at all in reaction to harmonic currents during GIC events.

According to a study by Zhang and Liu [66] on the significant impact of geomagnetic storms on the safety and stable operation of power systems, the analysis method of harmonics caused by excitation saturation related to GIC level, transformer type, parameters, and other factors is similar to that of DC bias caused by DC grounding the electrode current, which is limited in space and will not be described in detail. According to a study by Li *et al.* [95] that proposes a new reduced-scale model (RSM) equivalent circuit to reflect the actual operation of the UHV transformer under DC bias, the distortion of excitation current rises sharply as the DC bias current increases, with the first half cycle being the most affected. The even harmonics are caused by the DC bias current; the second harmonic virtually grows linearly with the DC bias current, whereas the growth rate of the high harmonics drops as the DC bias depth increases.

D. KEYWORD SUMMARY ON TRANSMISSION LINE

The harmonics components generated by GICs act in a variety of ways, and current detection systems do not take into account such complicated interference states that the effect of a geomagnetically-induced electric field on a power grid is taken to be equivalent to a set of voltage sources imposed on its transmission lines between various grounded points Liu *et al.* [96]. The integral of the geoelectric field along the line equals the magnitude of the voltage, converting the GIC computation into a circuit issue. The analysis suggests that the North European power transmission system is fairly resistant against extreme space weather events, according to a study by Piccinelli and Krausmann [76] that looked at the behavior of the Power System operational mode during geomagnetic storms. Only a few incidents of instability were detected in conjunction with an existing voltage instability due to the underlying system load when considering transformers more prone to geomagnetic storms.

According to a study conducted by Tozzi *et al.* [52] on how GIC amplitude varies with latitude during six major geomagnetic storms that occurred between 1989 and 2004, geomagnetically induced currents (GIC) can flow through infrastructure networks such as railroads, power transmission lines, and pipelines, causing damages ranging from slow degradation to immediate ruptures and malfunctioning. According to a study by Joo *et al.* [77] on the influence of geomagnetic disturbances on Korean electric power systems, the Korean electric power system meets the relevant standards in the United States and maintains system stability during a major geomagnetic disturbance. GIC neutral currents in transformers are calculated using the NERC's benchmark event, DC voltages, and GIC currents on transmission lines. The maximum GIC neutral is projected to be 51.13 A when Korean power systems are exposed to a 1.2 V/km geoelectric field, which meets the NERC requirement of 75 A as the maximum permissible current. The disparities between measurement and simulation can be detected in the zone of "rapid" fluctuation within seconds, according to a study by Halbedl *et al.* [10] that worked on actual results about geomagnetically induced currents (GIC) in the Austrian transmission system. Currents from underground railways that operate on DC flow through the transmission grid, according to a careful examination of the periods of occurrence. Constant expansion of energy networks, the growth of their interconnections, increased load, and conversion to low-resistive transmission lines, according to Belakhovsky *et al.* [59] study on the analysis of geomagnetically induced currents based on new characteristics to describe the variability of the geomagnetic field, increases the probability of emergencies during strong geomagnetic storms and substorms.

According to a study Gil *et al.* [97] on using time series and statistical analysis to determine the association between space weather and electrical grid breakdowns, intense solar phenomena disrupted transmission line productivity in southern Poland. The analyzed telluric field and observed GIC demonstrate a significant dependence on the induction response of the electrically conducting Earth join, according to a study by Sokolova *et al.* [98] on the correlation between space weather driven geomagnetic and telluric field variability with geoelectric and current induced in electrical grid states. The computed telluric fields exhibit a high connection with the observed GICs in Karelia's and the Kola Peninsula's power transmission lines. Important conclusions about the variability of geomagnetic and telluric fields in the region of central and eastern Fennoscandia connected to the GIC hazard might be drawn from a combined investigation of all three forms of changes. By using observations from the IMAGE magnetic observatories and the station for recording geomagnetically induced currents (GIC) in the electric transmission line in 2015, the study by Vorobev *et al.* [53] on analysis between variations of geomagnetic field, auroral electrojet, and geomagnetic induced current states examines relationships between geomagnetic field and GIC variations. High-altitude electromagnetic pulses (HEMPs) are bursts of electromagnetic energy in transmission line states, according to a study by Jeong [79]. A HEMP is made up of three components: E1, E2, and E3. E1 and E2 are instantaneous emissions that can harm electronic components, whereas E3 causes low frequency geomagnetically generated currents in transmission lines and power transformers. According to a study on GIC phenomena and their impact on power system operation by Bejmert *et al.* [80], a recorded case of transformer differential protection tripping due to GMD was detected using two algorithms that used rate of change of transformer differential currents and the DC component in the neutral current. To limit the influence of GIC, the two previously deployed methods in the power system either install capacitor neutral blocking on HV transformers or block capacitor banks in the high voltage transmission line.

According to a study Simpson and Bahr [99] on estimating the electric field response across Scotland using geomagnetic fields, magneto telluric impedances, and perturbation tensors, peak-to-peak electric field magnitudes in some areas of the

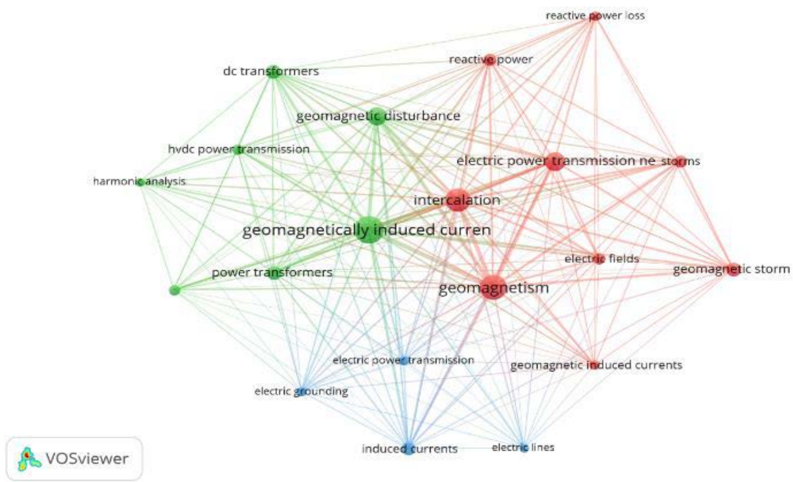

FIGURE 9. Scopus keyword network (min co-occurrence 33) NW 20 document.

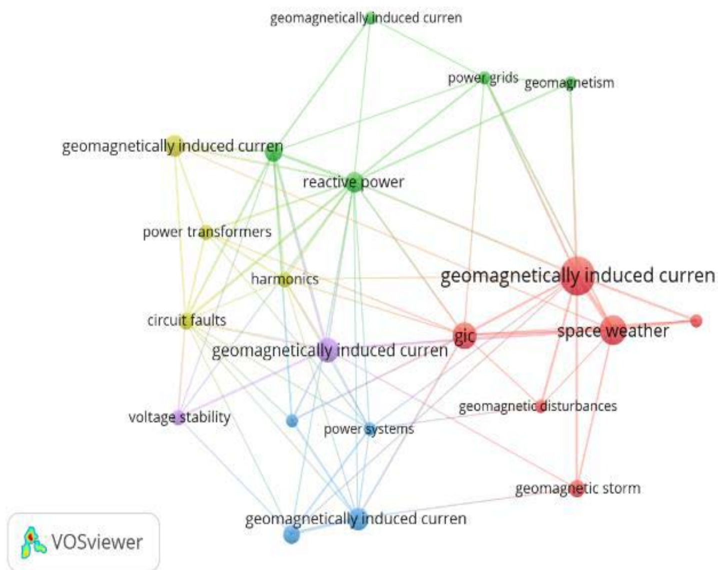

FIGURE 10. WoS keyword network (min co-occurrence 15) NW 19 document.

Scottish Highlands may have reached 13 V/km during the Halloween storm, with line-averaged electric fields bigger than 5 V/km sustained along some long-distance, high-voltage power transmission lines. According to a study Švanda *et al.* [72] looking for a rapid response of devices in the Czech electric distribution grid to disturbed days of high geomagnetic activity, the anomaly rate increases significantly immediately (within 1 day) after the onset of geomagnetic storms in the case of abundant series of anomalies on power lines. The increase in the anomaly rate is often delayed by 2–3 days in transformers. We also discovered that transformers and some electric substations appear to be vulnerable to substorm exposure, with a delayed increase in anomalies. According to a study Zawawi *et al.* [7] on the effects of GIC on selected 275 kV sub power system networks in Peninsular Malaysia, which is one of the low latitude countries, long duration with high magnitude GIC is the most hazardous to power transformers and could potentially cause major faults in the power system network. With a value of 315.10, a Neutral Earthing Resistor (NER) can be used to reduce GIC current flow in transmission line and thereby protect the power system network.

E. KEYWORD SUMMARY ON GROUNDING, ELECTRICAL FAULTY AND IMPROVEMENT

According to a study by Divett *et al.* [100] on calculating the modelled geoelectric field from the spectra of magnetic field variations interpolated from measurements during this storm and ground conductance using a thin sheet model, models to calculate GICs in the transmission network require two steps: I modelling the geoelectric field due to the combined effects of magnetic field variation during a storm

TABLE 8. Latest study on the estimation of the GIC in power network.

Paper	Title	GIC Identification Method in Power Grid	Country
(D. H. Boteler & Pirjola, 2017)	Modelling Geomagnetically Induced Currents	Develop and improved GIC modelling and outline two main network modelling approach that are mathematically equivalent	Canada
(Divett et al., 2018)	Transformer-Level Modeling of Geomagnetically Induced Currents in New Zealand's South Island	Calculated the GIC flowing through a single phase of every individual transformer winding in the network	New Zealand
(Clilverd et al., 2018)	Long-Lasting Geomagnetically Induced Currents and Harmonic Distortion observed in New Zealand during the 07-08 September 2017 Disturbed Period	Study period only longer-lasting GIC generated observable harmonics, but limited GIC impact from impulsive solar wind shock events	New Zealand
(Piccinelli & Krausmann, 2018)	North Europe power transmission system vulnerability during extreme space weather	Study analyzes the impact of extreme space weather on the northern part of the European power transmission grid for different transformer designs to understand its vulnerability in case of an extreme event	Italy
(Zirka et al., 2018)	Simplified models of three-phase, five-limb transformer for studying GIC effects	The study describes capabilities of a topological model of three-phase, five-limb transformer to accurately represent its response when subjected to geomagnetically induced currents	Ukraine
(Chisepo et al., 2018)	Measurements show need for transformer core joint details in finite element modelling of GIC and dc effects	To improve the finite element modelling of transformers subjected to dc excitation, by including core joint details	South Africa
(S. Nakamura et al., 2018)	Time Domain Simulation of Geomagnetically Induced Current (GIC) Flowing in 500-kV Power Grid in Japan Including a Three-Dimensional Ground Inhomogeneity	Simulation result shows that GIE exhibits localized, uneven distribution that can be attributed to charge accumulation due to the inhomogeneous conductivity below the Earth's surface	Japan
(Kazerooni & Overbye, 2018)	Transformer Protection in Large-scale Power Systems During Geomagnetic Disturbances Using Line Switching	Considers line switching as a remedial action to protect transformers from geomagnetic disturbances (GMDs)	United States
(Joo et al., 2018)	Assessment of the Impact of Geomagnetic Disturbances on Korean Electric Power Systems	Estimation of GIC Based on Geomagnetic Data over 20 years while using one-dimensional earth conductivity model	Korean
(Halbedl et al., 2018)	Geomagnetically induced currents modelling and monitoring transformer neutral currents in Austria	Estimation of the GIC based on Geomagnetic Field data and Comparison with the Real GIC measurement data using 1 dimensional earth conductivity model	Austria
(C. Liu, Wang, et al., 2018)	Quantitative influence of coast effect on geomagnetically induced currents in power grids: a case study	Comparison of GIC estimation by using 3D and 1D earth conductivity model and the Measured GIC Data	China
(Gil et al., 2019)	Does time series analysis confirm the relationship between space weather effects and the failures of electrical grids in South Poland?	Apply Time Series and statistical Analysis study on Failure of the Electrical Equipment due to the Formation of the GIC	Poland
(Sokolova et al., 2019)	Space-Weather-Driven Geomagnetic- and Telluric-Field Variability in Northwestern Russia in Correlation with Geoelectrical Structure and Currents Induced in Electric-Power Grids	Study the northwestern Russia Geoelectric and Induced Current value based on the Geomagnetic and Telluric Field	Russia
(Vorobev et al., 2019)	Statistical relationships between variations of the geomagnetic field, auroral electrojet, and geomagnetically induced currents	Study the impact of the Geomagnetic field and Auroral Electrojet on GIC formation	Russia
(Jeong, 2019)	Vulnerability Assessment of Korean Electric Power Systems to Late-Time (E3) High-Altitude Electromagnetic Pulses	Study the Impact of the High-Altitude Electromagnetic Pulses (HEMPs) on the formation of the GIC in Korean Electric Power System	Korea
(Nahayo et al., 2019)	Observations from SANSA's geomagnetic network during the Saint Patrick's Day storm of 17–18 March 2015	Analyzed the correlation between a modelled induced electric field and measured geomagnetically induced currents in Southern Africa	South Africa
(Li et al., 2020)	Analysis of the DC Bias Effects on the UHV Autotransformer with Rated Load Based on a Reduced-Scale Model Experiment	Study the effect of the DC Bias from GIC formation onto the High Voltage Transformer	China
(Schühle & Tenbohlen, 2020)	Calculation of geomagnetically induced currents based on a three-dimensional conductivity model	GIC calculation based on 3D earth conductivity	Russia
(Simpson & Bahr, 2020)	Estimating the electric field response to the Halloween 2003 and September 2017 magnetic storms across Scotland using observed geomagnetic fields, magneto telluric impedances and perturbation tensors	Multiply magneto telluric (MT) impedances from 23 sites in Scotland and northern England with measured geomagnetic field spectra from the Halloween 2003 and September 2017 storms to estimate maximum peak-to-peak, electric field magnitudes and directions for these storms	Germany
(Poedts et al., 2020)	European Heliospheric Forecasting Information Asset 2.0	Validating the upgraded EUHFORIA/SEP model, it will be coupled to existing models for GICs and atmospheric radiation transport models	Belgium
(Bejmert et al., 2020)	HV Transformer Protection and Stabilization under Geomagnetically Induced Currents	Study the DC excitation of power transformers due to geomagnetically induced currents (GIC)	Poland

and varying ground conductance, and (ii) using a network mode. According to a study Klauber *et al.* [8] on the consequences of geomagnetically induced currents (GICs) and effective mitigation measures during GMD, ground

TABLE 8. *(Continued.)* **Latest study on the estimation of the GIC in power network.**

(Švanda et al., 2020)	Immediate and delayed responses of power lines and transformers in the Czech electric power grid to geomagnetic storms	Study the delay exposure of power-grid due to strong geomagnetically induced currents	Czech Republic
(Juusola et al., 2020)	Induced currents due to 3D ground conductivity play a major role in the interpretation of geomagnetic variations	3D ground conductivity for GIC estimation	Finland
(Beggan et al., 2021)	Geoelectric field measurement, modelling, and validation during geomagnetic storms in the UK	Conduct the measurement to compute the magneto telluric impedance transfer function at the selected location to predict the amount of geoelectric field	Ireland
(Zawawi et al., 2021)	Analysis of a geomagnetic induced current on a three-phase power transformer and power system	Study the effect of GIC on three-phase transformer includes half-cycle saturation and reactive power consumption	Malaysia
(Khurshid et al., 2021)	Geomagnetic Induced Current modelling and analysis on high voltage power system	Conduct GIC analysis based on modified IEEE-18 bus test system by applying GMD at the system	Malaysia
(Burhanudin et al., 2021)	Measurement on the Geomagnetic Induced Current (GIC) at low latitude region in Malaysia	Study the existent of geomagnetic induced current (GIC) in Malaysia based on measurement	Malaysia
(Ebihara et al., 2021)	Prediction of geomagnetically induced currents (GICs) flowing in Japanese power grid for	Evaluate the lower limit of the GICs that could flow in the Japanese power grid against a Carrington-class severe magnetic storm	Japan
(Pilipenko, 2021)	Space weather impact on ground-based technological systems	Provides information on the main characteristics of geomagnetic field variability, on rapid field variations during various space weather manifestation	Russia
(Yagova et al., 2021)	Spatial scale of geomagnetic Pc5/Pi3 pulsations as a factor of their efficiency in generation	To quantify the efficiency of GIC generation by geomagnetic pulsations, a ratio between power spectral densities of GIC and magnetic field variations is introduced	Russia
(Reiter et al., 2021)	Statistics of large impulsive magnetic events in the auroral zone	Study the impact of the large impulsive magnetic event on harmonic activity at the hydro-Quebec power system	Canada

conductivity models are used to transfer magnetic field data to electric field data.

According to a study by Zhang and Liu [70] on installing additional resistors in the transformer neutral points of high-risk nodes to even the GIC distribution in whole networks and make the theoretical calculation of GIC in East China 1000kV power grid after installation, geomagnetic storms and grounding current of DC electrode in converter stations have similar effects in China's 500 kV high-voltage DC network and 800 kV ultra-high voltage DC power transmission system. The study Zhang and Liu [66] proposes an evaluation approach based on studied technical criteria for power system safety during geomagnetic storms states that the Earth's electric field is induced on the Earth's surface according to Faraday's law of electromagnetic induction. The potential difference between different grounding points in the power system, because of the Earth's electric field, will drive GIC in the power system, which will flow through the neutral point and winding areas of the power transformer, resulting in saturation of the half wave of the transformer core, resulting in voltage transformation.

According to a study by Abda *et al.* [69] that reviewed the literature on space weather, geomagnetic disturbances (GMDs), and geomagnetic interference (GICs) and their impacts on power systems in both high and mid-low latitude regions, the impact of this complicated interaction causes the magnetic field on the ground to rapidly change. A geoelectric field is induced on the Earth's surface because of this variation, causing a geomagnetically induced current (GIC). The power station/substation nodes are connected by line resistors and earthed through earth ground resistors using line and grounding resistance values provided by Trans power New Zealand Ltd, according to a study by Mukhtar *et al.* [101] on the calculation of GIC in substations and individual transformers based on geomagnetic activity. According to the calculations for the 2003 storm, GIC more than 10 A may persist for lengthy periods at some spots, causing severe harmonic distortion and maybe localized transformer heating.

According to a study by Caraballo *et al.* [71] on modelled GIC using a uniform conductivity for the entire Mexican territory and spatially uniform geomagnetic disturbance, the presence of thousands of kilometers of coastal power lines may favor the development of large GIC due to the ground conductivity contrast between the oceans and continental landmass. Haddadi *et al.* [82] conducted a cross-examination of the outcomes of the load-flow-based (LF), transient stability type (TS), and electromagnetic transient type (EMT) approaches. The goal is to identify their limitations, assess the consistency of their results, and provide assumptions on how to use them for GMD system impacts analysis. The electric field induces an induced voltage in transmission lines, which causes low-frequency (0.1 Hz or lower) Geomagnetically Induced Currents (GICs) to flow through transmission lines and grounded transformers to ground. According to a study by Behdani *et al.* [74] on the analysis of the power transformer ferro resonance phenomenon due to GICs in series capacitor compensated networks, the effects of various involving parameters such as system loading, compensation level, and substation grounding resistances on the occurrence of ferro resonance due to GICs are evaluated using an example test system in the EMTP-RV environment. The findings show that GICs can significantly increase the vulnerability of power transformers to ferro resonance phenomena in series capacitor compensated power networks. Fig. 9 and Fig. 10 shows the top Scopus and WoS network used by the authors.

F. KEYWORD SUMMARY ON THE ESTIMATION OF THE GIC IN POWER NETWORK

All Based on the Bibliometric study, the study on GIC in power network keep on growing in the form of measurement and calculation. The study in the GIC field started to be explored by middle and low latitude region due to the impact and harmful effect it possesses despites the impact from the GIC is more severe in high latitude region. The study on the GIC based on the simulation and measurement in the power network could benefits in the following ways:

- The study on the GIC in Power Network is correlated to the activity of the solar storm and geomagnetic disturbance
- The estimation of the GIC is estimated based on simulation and measurement data of the geomagnetic disturbance from the local magnetic field data before comparing with the real-time measurement
- The study on the GIC in Power Network is usually linked to the anomalies within the power system such as transformer breakdown, high reactive power, harmonic, and electrical faulty
- In Estimating GIC, the purposes are to mitigate the level and threshold of the GIC and finding the possible way to mitigate the level of the GIC which possess harmful effects on the Power System

In conclusion, the earliest publication on the study on the GIC in the power network by using the search keyword can be track back since 1979 in Scopus and 1992 in WoS. Based on the Study on GIC in Power Network, the earliest study on the GIC in power network is only perform by the country in high latitude region such as Canada [92], [102], [103] and Finland [104], [105] follow by middle latitude region such as China [3], [70], [106], Italy [1], [52] and Japan [107]–[110] and low latitude region such as Australia [111], [112] and Malaysia [69], [113] Calculating GIC based on constructing a model of the AC transmission system for quasi-DC frequencies of the GIC, the GICs through transformers can be determined for various geomagnetically induced Earth-Surface-Potentials (ESP) using Electro-Magnetic Transients Program [20]. (EMTP). The study's goal is to discover Harmonics and Switching Transients in the presence of GIC. The transient performance of the Current Transformer (CT) is researched by [26] in order to ascertain the reduced time-to-failure. The relay mis operation existed in two conditions: erroneous CT response and GIC interaction with large power transformers with differential protection, according to saturation from a combination of GIC and DC fault offset. Langlois *et al.* [114] did a study on the calculation of the GIC at Abiti, Quebec, where they monitored the electric and magnetic fields at a rate of 8640 points per day for 500 days and discovered that the electric fields occur with a probability inversely. The driven GIC software was used in a research by Hannett *et al.* [35] to investigate mitigation concepts such as the impacts of line outages, line series capacitors, and transformer neutral blocking resistors. While Lu and Liu [38] used a finite element (FEM) simulation of a transformer to identify geomagnetically induced currents, Lu and Liu [38] utilised a finite element (FEM) simulation of a transformer to identify the geomagnetically induced currents (GIC). The geomagnetically induced currents and local geomagnetic fluctuations were recorded simultaneously at the neighbouring Nurmijarvi Geophysical Observatory, according to a paper by Viljanen [115] titled Relation of Geomagnetically Induced Currents and Local Geomagnetic Variations. Here are two models for calculating GICs from the magnetic field's time derivative.

The earth's conductivity is used as a fitting parameter in a plane wave model with a homogenous earth. Mckay and Whaler [116] used magneto telluric (MT) data in the form of MT tensors to estimate the size and spatial distribution of the electric field in northern England and southern Scotland with the goal of predicting the flow of geomagnetically induced currents (GIC) in power networks in the region. According to a study conducted by Viljanen *et al.* [117] on the relationship between substorm characteristics and rapid temporal fluctuations of the ground magnetic field, significant dH/dt occur predominantly during the substorm beginning when the amplitude of the westward electrojet rapidly grows. The effects of interactions between stations on the calculation of geomagnetically induced cur-rents in an electric power transmission system Pirjola [63] looks at the effects of off-diagonal elements of the earthing impedance matrix, i.e. the effects of interactions between different stations, in greater detail and quantitatively. The first GIC study in Brazil was conducted by Trivedi *et al.* [42], who discovered that during a significant geomagnetic storm on November 7th to 10th, 2004, the GIC amplitudes, measured using geomagnetic fluctuations in 500 kV power transmission lines in the S-E region of Brazil, were about 15 A. Comparison of magnetic-storm recordings and observed transformer neutral current data reveals that the disruptions were produced by geomagnetically induced currents, according to a study by Liu *et al.* [43] on Geo-magnetically Induced Currents in the High-Voltage Power Grid in China (GICs).

The GIC level at the Ling'ao nuclear power plant is higher than at the Shanghe substation, according to the statistics. The cause is thought to have something to do with the grid structure and the coast effect. According to a study conducted by Wu *et al.* [118] to clarify and measure the risk from GMD represented by geoelectric field, method for analysis of relationship between voltage stability of long-distance transmission system and the size and direction of geoelectric field, the results show that the method is feasible, and the index can reflect the relationship between the

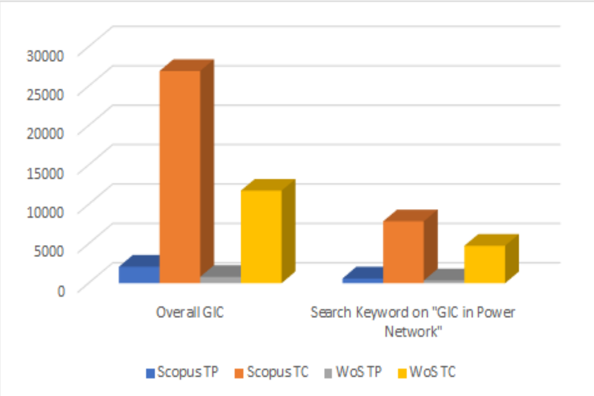

FIGURE 11. The respective comparison between the publications and citations counts of "GIC" and "estimation of the GIC in the power network."

long-distance transmission system voltage stability and the geoelectric field, and the set of the indices. Reliable estimates are obtained, and the modelling are found to explain up to 90% of the measurements, according to a study conducted by Püthe *et al.* [119] from Switzerland on 3-D modelling of induction processes in a heterogeneous Earth and the construction of a magnetospheric source model described by low-degree spherical harmonics from observatory magnetic data to calculate GIC.

According to a study conducted by M. Nakamura *et al.* [48] on statistical estimation of extreme aurora electrojet activities, statistical evidence for finite upper limits to AL and AU, estimate the annual expected number and probable intensity of their extreme events, and detect two different types of extreme AE events is an important factor in space weather research. The new technique helps mitigate the zero sequence current flowing through the neutral of transformers during unsymmetrical faults, according to a study by Hussein and Ali [50] from the United States on a new approach by using a controlled resistance to suppress the GIC flowing through the neutral of transformers. The preliminary electric field predictions of studied by Bonner and Schultz [120] are compared to previously recorded time series, idealised transfer function scenarios, and existing industrial data. Some limitations, such as long period diurnal drift, are addressed, and solutions are suggested to further improve the method before direct comparisons with actual GIC measurements are made, according to -try methods to assess the validity of the algorithm for potential adoption by the power industry. In recent years, there has been a lot of progress in the research of GIC in Power Networks. Table 8 shows some of the latest study on the GIC in the Power Network.

G. FUTURE TREND

All The field of "Estimation of the GIC in the Power Network" have been adopting 3D earth conductivity model to replace the 1D conductivity model as it is more accurate and efficient in estimating the GIC level. There is also the research on time-series and statistical analysis study on the failure of the electrical equipment due to GIC. This method involves identifying the time of the GMD impact and the time it takes to cause the breakdown to the electrical equipment from the Power System Network. There is also the study on impact of the High-Altitude Electromagnetic Pulses (HEMPs) on the formation of the GIC in Korean Electric Power System which is new to the field. There is also the study on the delay action of the exposure of the power grid due to the strong geomagnetically induced current. Looking at the current scenario, this trend is expected to expand shortly and studied in various countries to identify the threshold limit of the GIC on the power network. The latest study provides the possibility of identifying the reason behind the electrical equipment failure in the power network by applying time-series analysis, improved the calculation method on the GIC by using 3D ground conductivity, and study any related impact which might generate backflow current from the underground other than the impact from the GMD such as HEMPs.

VI. CONCLUSION

This paper is a unique collection of the bibliometric study and recent development in the field of "Estimation of the GIC in the Power Network". Bibliometric study helped to discover the hidden structures of the publications in this area. Over the years, development in the field of "Estimation of the GIC in the Power Network" have gained tremendous attention from the research community. Out of 601 publications in Scopus, around 71.04% (TP = 427) of publications came since 2013 and WoS around 75.1% (TP = 268). Overall total citation of 7862 and 4761 for since 1979 for Scopus and 1992 for WoS. The most productive author for Scopus is Liu, L while WoS is Pirjola, R. Most of the work in Scopus is produced in Engineering and Energy discipline while WoS is Engineering and Meteorology Atmospheric Sciences. Space Weather is the journal with maximum publication followed by IEEE Transactions on Power Delivery.

The United States remains at the top position for Scopus and WoS in terms of number of publications in country wise analysis. In the Institution wise analysis, North China Electric Power University stands at the top in Scopus and Finnish meteorological institute remains at top in WoS. Then, the comparative analysis of "Estimation of the GIC in the Power Network" domain is performed from the context of the most influential papers in this field. This analysis could provide a clearer and better perspective for the new researchers. Research works on "GIC" has evolved over the years as it can be seen from the indexing by Scopus and WoS. Till now (from 2009), there are 2094 publications in "GIC" as indexed by Scopus and 809 publications indexed by WoS.

These publications have received a total of 26937 citation in Scopus and 11749 citations for WoS, which specifies the significance and wider acceptability of the "GIC" domain. However, in the case of "Estimation of the GIC in the Power Network" publications, there are only 601 and 357 for Scopus and WoS publications with only 7862 citation counts for Scopus and 4761 citation count for WoS. Fig. 11 shows the respective comparison between the publications and citations count of ''GIC'' and ''Estimation of the GIC in the Power Network''. We can observe that there is a huge gap between the publications on general ''GIC'' research and ''Estimation of the GIC in the Power Network'' research. Therefore, one of the major limitations of this study is the available numbers of papers in ''Estimation of the GIC in the Power Network''. However, this also limelight's the immense scope and need for more and more research in the domain of ''Estimation of the GIC in the Power Network''. The future scope of this study may entail the more depth analysis with other indexing databases such as GIC effect on pipeline system.

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KHARISMI BURHANUDIN received the bachelor's and master's degrees from Universiti Teknologi MARA, Malaysia, where he is currently pursuing the Ph.D. degree. He is conducting research on space weather perturbation impact on geomagnetic induced current (GIC) at Malaysian Power Network.

MOHAMAD HUZAIMY JUSOH (Member, IEEE) received the bachelor's degree in electronic engineering from Universiti Teknologi MARA (UiTM), Shah Alam, Malaysia, in 2004, and the Doctor of Engineering degree from Kyushu University, Japan, in 2013. He is a Senior Lecturer. He is currently employed as the Senior Director and the Director for Satellite Communication with the College of Engineering, UiTM. His research interests include space and earth electromagnetism, polar exploration, MAGDAS, and satellite communication.

ZATUL IFFAH ABDUL LATIFF (Member, IEEE) received the bachelor's degree in electrical engineering from Korea University, in 2010, and the master's degree in telecommunication and information engineering from Universiti Teknologi MARA (UiTM), in 2013. She is one of the MAGDAS network's co-researchers and is responsible for monitoring and maintaining one of the network's observatories in Johor, Malaysia. She is a Lecturer with Malaysia's Universiti Teknologi MARA's Faculty of Electrical Engineering.

MOHD HELMY HASHIM is currently pursuing the Ph.D. degree with Universiti Teknologi MARA. He is a Research Officer for the Malaysian Space Agency (MYSA) and has worked on several research projects, including the MAGDAS Station at the Langkawi National Observatory (LNO), Universiti Sains Malaysia (USM). He is an expert in space weather research and collaborates with the Kyushu University's Space Environment Research Centre.

NUR DALILA KHIRUL ASHAR (Member, IEEE) received the Diploma and B.Eng. degrees in electrical engineering from Universiti Teknologi MARA, Malaysia, in 2007 and 2010, respectively, and the M.Sc. degree from the Department of Electrical Engineering (Computer Control and Automation), National University of Singapore (NUS), Singapore, in 2013. She is currently pursuing the Ph.D. degree with the Faculty of Engineering, Universiti Putra Malaysia. She has been with Universiti Teknologi MARA, as a Senior Lecturer. Her main research interests include machine learning and space weather.