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Abstract

This paper describes the application of data mining techniques for eludicating patterns and trends in the field of Distributed Generation (DG). The emphasis is on the use of bibliometric methods, *viz* techniques which focus on trends in the publication of text documents rather than the content of these documents. Of particular interest is the relationship between publication patterns, as characterized by term occurrence frequencies, and the underlying technological trends and developments which drive these trends. While focusing on research in DG provides a concrete focus for our discussions and experiments, the general approach and techniques used are applicable to a broad range of industries, situations, and locations. The results obtained help to highlight salient trends in the evolution of DG-related technology focus areas and clearly indicate that interesting information and conclusions can be derived from this line of analysis.

Keywords: bibliometrics, distributed generation, technology mining

1. Introduction

The planning and management of research and development activities is a challenging task that is further compounded by the large amounts of information which researchers and decision-makers are required to sift through. Information

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regarding past and current research is available from a wide variety of channels (important examples include publication and patent databases), providing both a difficult challenge and a rich source of possibilities. On the one hand, sifting through these databases is time consuming and subjective, while on the other, they provide a rich source of data with which a well-informed and comprehensive research strategy may be formed.

Using bibliometrics to study the progression of research and technological development is not a new idea and there is already a significant body of research addressing this problem (for a good review, the reader is referred to [1, 2, 3, 4]. Interesting examples include visualizing the inter-relationships between research topics [1, 5], identification of important researchers or research groups [6, 3], the study of research performance by country [7, 8], the study of collaboration patterns [9, 10, 11] and the prediction of future trends and developments [12, 13, 14, 5]. Nevertheless, given the many difficulties inherent to these undertakings, there is still scope for further development, as well as for testing and fine-tuning these methodologies via appropriately scoped pilot studies. The research described in this paper was motivated by, and seeks to address this need.

To focus discussions and to provide a concrete domain on which bibliometrics can be suitably applied, a case study was conducted on the domain of distributed generation (DG). Broadly speaking, DG are generation sources that are connected to the distribution system close to the load point. Distributed generation could be classified into two main types; renewable such as wind and solar or non-renewable such as diesel generators and micro-turbines. The increasing penetration of DG in distribution systems coupled with the growing interest among the electrical power engineering community to meet environmental and energy efficiency constraints resulted in an increasing interest in DG. Thus, distribution systems world-wide are experiencing significant changes and challenges due to the increasing penetration of DG.

In general, distribution systems are radial in nature, meaning that power flows in one direction from the main substation to the load point. The addition of DG on the distribution system transforms the distribution system into a multi-source system. Topics such as distribution system protection, control and stability, which were considered simple and easy to design for distribution systems, have now become complex and of major importance [15, 16, 17]. The planning and reliability of the distribution system will be affected with the addition of DG sources [18, 19, 20, 21]. In addition, new concepts and operational issues have emerged from this new distribution system structure which includes smart grids, micro-grids and islanding detection [22, 23, 24].

As such, while DG research provides a well-defined scope in which to conduct our analysis, it still spans a wide range of technical areas and promises to be a rich and challenging problem domain on which to conduct our analsis. In addition, we note that bibliometric analyses have been conducted on a variety of energy related issues (for e.g.: energy research in general [25], power sources [26], biofuels [27]), but not in the DG domain. As will be demonstrated, the application of bibliometric techniques can be extremely helpful in highlighting the main directions among the power engineering community in the area of DG.

The rest of the paper is structured as follows. The current section presented the background and motivations for the research, while Section 2 details the data collection and research methodology used. In Section 3 the main results along with preliminary observations are described. Section 4 analyzes these results in the context of specific developments and trends within the DG domain. Section 5 concludes the paper by summarizing the main findings and presenting suggestions for future areas of research.

2. Methods and data

The main aim of this study is to investigate the use of bibliometric techniques for studying technological innovation relevant to DG. These are techniques which focus on patterns and trends of textual information, rather than on the actual content of the text to be analyzed.

To conduct the pilot study, we first collect a set of records consisting of journal and conference publications relevant to the field of distributed generation. To do this, the following keywords were collected based on consultation with a subject-matter expert and were submitted to the Scopus database through its web interface (as a title/abstract search):

- **“distributed generation”**
- **“dispersed generation”**
- **“distributed resources”**
- **“embedded generation”**
- **“decentralized generation”**
- **“decentralized energy”**
- **“distributed energy”**
- **“on-site generation”**

Searching for these keywords returned a total of 4734 records, which were saved to a database and used to represent the body of research in DG.

As our objective is to study the evolution of individual sub-fields within the broad context of DG, the next task was to identify subsets of this body of research, linked to representative keywords or search terms. This mechanism is then used to study the general growth and direction of the DG domain. We discuss this in terms of the following three-stage process:

1. Identification of comparable topics or technologies.
2. Extraction of relevant/related studies.
3. Normalization and preprocessing.

2.1. Distributed Generation: topics and themes

In order to obtain results that are interesting and useful, it is important that our analysis of the publication data is appropriately framed. For example, comparing the relative growths of two sub-areas of DG would only make sense if the two areas were somehow competitive with each other, or were at least similar in some sense. At the same time, the field of DG research is quite broad and involves a variety of interesting problems and challenges. To allow for this diversity, we define three separate dimensions in which to conduct our analysis:

1. **DG technology -** i.e. part of the attraction of using a DG system is that it allows energy from a variety of localized sources to be integrated into the grid. As such, one way of decomposing the field of DG research is in terms of the technologies for generating this electricity. In [28], a comprehensive survey on the different DG types and technologies was presented. Based on [28], some of the most dominant DG technologies include wind turbines, photovoltaic, fuel cells and micro-turbines. Towards this end, we choose to study the following four topics: (1) *Wind* (2) *Microturbines* (3) *Solar PVs* (4) *Fuel Cells*
2. **DG interfaces -** another important component of a DG system is the interface to the utility grid or to the customer. As highlighted in [29], almost all DG can be grouped into three main types, according to the type of interface, which includes inverter, induction and synchronous. Thus, publication patterns for the following three classes of DG interfaces will be analyzed: (1) *Inverter based* (2) *Synchronous based* (3) *Induction based*
3. **General studies -** besides the above two categories, research in DG also spans a range of other challenges and issues. The third dimension in our analysis groups a number of these topics: (1) *Control* (2) *Reliability* (3) *Islanding detection* (4) *Planning* (5) *Stability* (6) *Power quality* (7) *Electricity markets/economics* (8) *Protection* (9) *Forecasting* (10) *Micro-Grids/Smart grids.*

To provide additional depth and breadth to our study, we supplement our results with two further forms of analysis:

1. To elucidate more detailed trends in the DG domain, the database is further "sliced and diced" by searching for occurrences of terms in the second dimension (inverter, synchronous and induction based) within the context of the topics listed in the third dimension.
2. High level statistics regarding the distribution of publications amongst countries and journal titles are also presented to give a broader perspective of the current state of DG research.

2.2. Data extraction

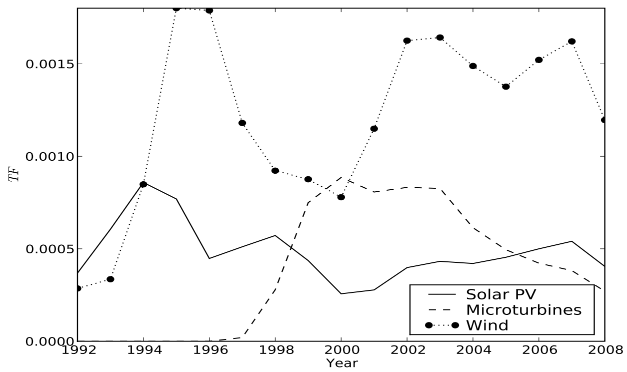
Once the initial database is constructed, patterns and trends of individual research topics can be easily extracted and graphed using a combination of appropriate SQL queries and regular expressions.

In general, we are interested in the level of research activity or interest in a particular topic, as reflected in a representative keyword. Of course, the true research activity is unobservable, but we postulate that the *frequency* at which a particular term appears in the academic literature, henceforth referred to as the *term frequency*, can serve as a proxy variable for this interest. Note that using the term occurrence counts in this way is not a new idea (for relevant examples, see [30, 31, 32]) though the exact form by which the term frequency is calculated may differ slightly. Certainly, given that the academic literature is the primary channel through which research findings are disseminated, it is reasonable to expect that the term frequency approximates the rate at which research on a particular topic is generated.

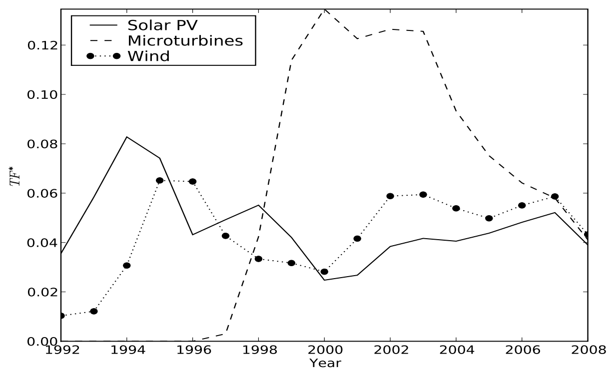
To illustrate this process, we briefly consider the three topics: {"solar PV", "microturbine" and "wind"}. To monitor development in these three sub-fields, the abstracts for all of the records in our database are compiled and grouped according to year of publication. Regular expressions corresponding to the three terms above are created and used to search the annualized abstract collections. To obtain a measure of term frequency for a term $\mathcal{T}_i$, the number of occurrences of this term for a given year are counted then normalized by the total number of words in all of the abstracts in the year as follows:

$$TF_i(t) = \frac{n_i}{|\mathcal{A}_t|} \tag{1}$$

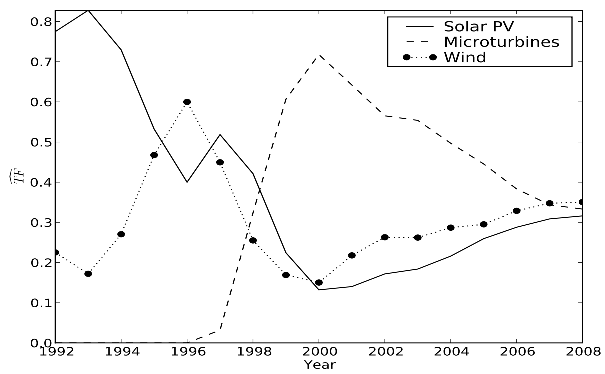
where n_i is the number of occurrences of term $\mathcal{T}_i$ in all abstracts published in the year t, and $\mathcal{A}_t$ is the string formed by concatenating all the words in the abstracts in that same year. These terms are graphed and are shown in figure 1(a).



(a) Unnormalized



(b) Topic-wise normalization



(c) Topic-wise & cross-sectional normalization

Figure 1: Term frequencies for "solar PV", "microturbine" and "wind"

2.3. Normalization and post-processing

One problem with using the raw frequencies in this way is that it tends to favour terms which are very general in nature, such as “wind” in this case, over terms which are very specific like “microturbine”. In Fig. 1(a), it can be seen that the line for “wind” is a lot higher than the other two lines. However, this could simply be because wind energy is indeed a common form of renewable energy (which in the US and EU exceeds solar power in terms of its share of electricity generation [33]). The larger term frequencies for “wind” are hence a straightforward reflection of this fact. In addition “wind” is also a very general term which occurs frequently in common usage while “microturbine”, for example, is a very specific term used exclusively to refer to a particular device.

In many cases we are less concerned with the absolute value of TF than with the overall *trend* observed in these figures - a low absolute value for TF may be secondary to the fact that these values are doubling every year, for example. To better observe these trends, we define TF^*, a normalized form of TF:

$$TF_i^*(t) = \frac{TF_i(t)}{\sum_{j=1992}^{2008} TF_i(j)} \tag{2}$$

Doing this for the three topics listed above results in the graph in Fig. 1(b). From this subfigure, it can be seen that, if we disregard the absolute values, it would appear that “solar PV” and “wind” have very similar trends over the last 16 years, while research in microturbines experienced a very sharp increase in research activity between 1996 and 2000, remained relatively stable for a few years, then started dropping again from 2003 onwards (while this same information was present in the first graph it is evident how appropriate normalization allows different aspects of the data to be more easily noticed).

Finally, an alternative form of normalization was considered:

$$\widehat{TF}_i(t) = \frac{TF_i^*(t)}{\sum_{j=i}^{m} TF_i^*(t)} \tag{3}$$

where m is the number of topics being studied concurrently. This would hopefully allow the growth in the different research areas to be more easily compared.

When applied to the three topics from above, the graph in Fig. 1(c) is obtained. Note that, while this graph is quite similar to Fig. 1(b), there is an important difference early on in the graph where, in Fig. 1(c), the plot for solar PV related research is seen to be starting from a high value and slowly decreasing while for wind the curve shows an early rise in $\widehat{TF}$. This highlights the fact that, while both topics can be seen gaining in popularity early on, the $\widehat{TF}$ for "wind" gradually gains on solar PV and exceeds it by around 1995.

In brief, what we seek to demonstrate is not that any one of these graphs are necessarily "correct" or "wrong", but that different forms of normalization highlight different aspects of the data. As such, there is value in considering all the different forms of normalization when conducting our analysis.

2.4. Implementation

The required computational tools were implemented using the Python programming language and the SQLite database engine, as these facilitated faster development. The former also includes a broad selection of libraries, including those useful for the analysis of text and for data collection from the WWW. Both products are also cross-platform and open-sourced, which allowed applications to be deployed on a range of different operating systems and environments, and at a very low cost.

3. Results

The data collected from the Scopus database is used to generate yearly frequency values for the research areas listed in section 2.1. In addition, a three-tap gaussian filter was used to smooth the resulting time series as this was quite noisy and in some cases the number of publications retrieved were quite low. This is a reasonable pre-processing step because the research which results in a publication would have been carried out over a period of time prior to the appearance of the publication; as these publication counts are in fact a proxy for the underlying research activities, smoothing the raw data in this way also serves as a means of taking this spread into account.

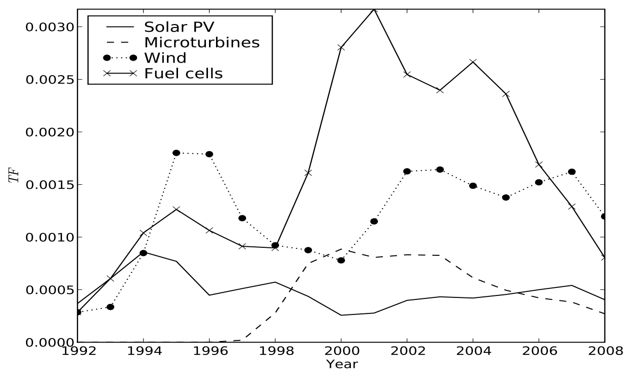
Four different sets of graph are presented here, corresponding to the three "dimensions" described in section 2.1 (dimension three comprised a large number of topics and was split into two sets of topics); these are presented in Figs. 2 to 5. In the following subsections, the initial observations are noted and discussed. In section 4 a more detailed analysis will be presented, which will take into account the underlying drivers within the field of DG.

3.1. DG technology (Fig. 2)

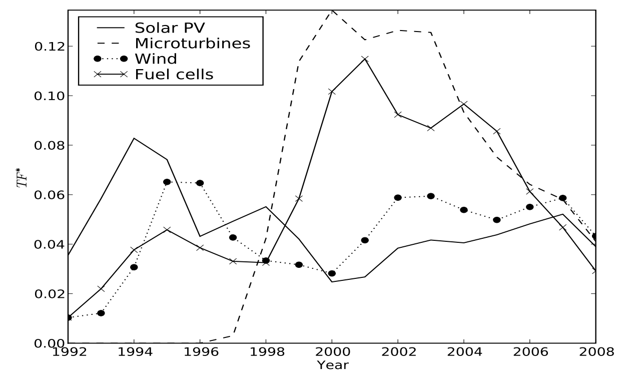
1. As with the example described in section 2 (in Fig. 1), the results varied significantly when subjected to the different normalization schemes. In general, the normalized data tended to show underlying trends with more clarity. However, using cross-sectional normalization appeared to produce noisier curves.
2. One prominent trend which was consistent across the three versions was with micro-turbine research, which exhibited a marked increase in term frequencies between the years 1996 and 1999, before levelling off and finally declining again. Research in fuel cells also showed a similar trend though the term frequencies in this case started from a higher point compared to the plot for microturbine.
3. In the case of solar PV, a "V" shaped curve centered around the year 2000 was observed. While this is most prominent in Fig. 2(c), it can be discerned in all three graphs and is consistent with general trends in the field of solar PV research [34].

3.2. DG interface technologies (Fig. 3)

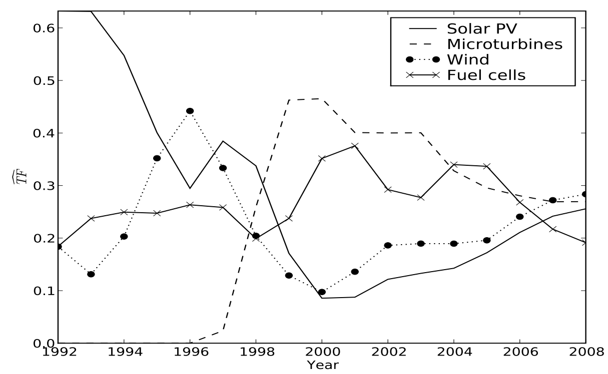
Two broad trends which were observed was with the term frequency plots for Inverter and Synchronous interfaces - specifically, over the period of analysis, research in synchronous interfaces seems to have declined somewhat, with the transition point falling somewhere between 1996 and 1998. In contrast, research in inverter-based interfaces showed the exact opposite trend - the term frequencies for "inverter" started out low but increased sharply at or around the year 1998.



(a) Unnormalized

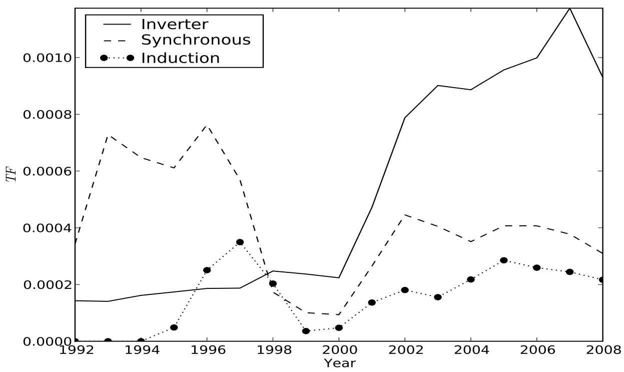


(b) Topic-wise normalization

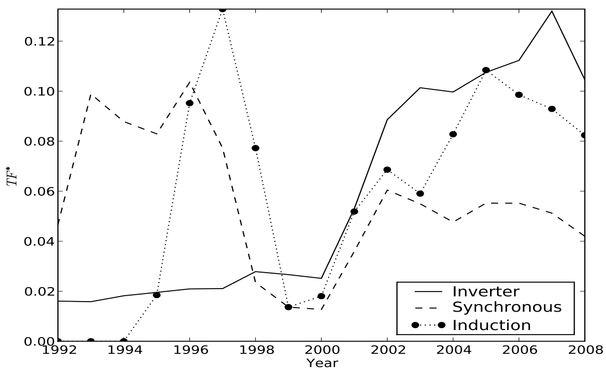


(c) Topic-wise & cross-sectional normalization

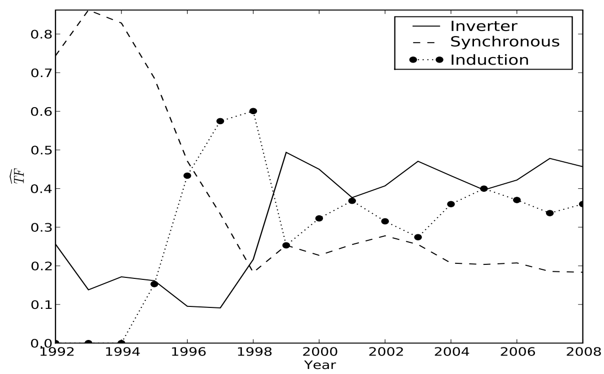
Figure 2: DG technology



(a) Unnormalized



(b) Topic-wise normalization



(c) Topic-wise & cross-sectional normalization

Figure 3: DG interfaces and technologies

For induction-based interfaces, the trend is less clear but broadly, research in this topic is seen increasing gradually throughout the analysis period, starting from around 1994.

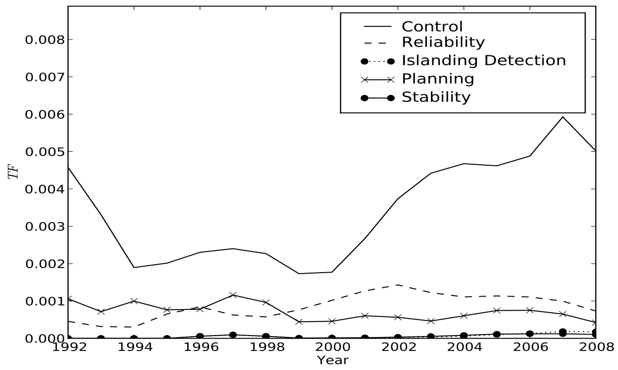
3.3. General studies (Figs. 4 and 5)

This dimension included a large number of topics, which were further divided into two separate figures (Figs. 4 and 5) to facilitate interpretation and analysis of the results. The division into the two batches was done randomly, where the only aim was to reduce the clutter within individual graphs.

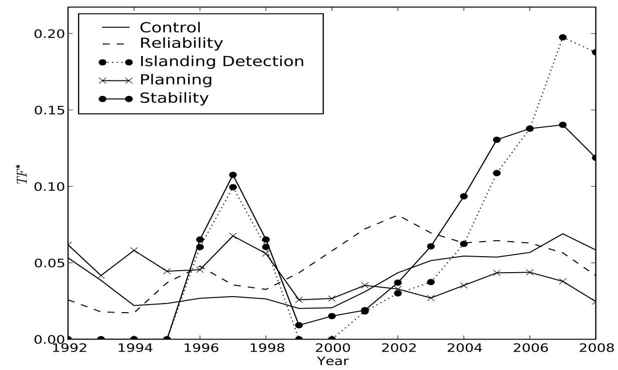
Batch 1 - {Control, Reliability, Islanding, Planning, Stability} (Fig. 4)

1. There are a number of prominent trends in this first batch of topics. One interesting example is with research in "islanding"; in Fig. 4(a), this plot can hardly be seen as its overall term frequency is quite low. However, when either of the two normalization schemes are applied, it is immediately clear that this is in fact one of the fastest growing topics of research from amongst this batch of topics.
2. A similar pattern is observed with "stability", with the TF^* and $\widehat{TF}$ curves showing sharp increases at or around the year 1997, but decreasing somewhat for the next few years before again starting to increase sharply.
3. Research interest in "planning" starts out with relatively high term frequencies, but these gradually decrease over the analysis period.
4. Another interesting example is in the case of "control" - where the values of TF and TF^* for this topic (Figs. 4(a) and 4(b)) are seen increasing quite steadily; however, when normalized with respect to the other topics ($\widehat{TF}$ - Fig. 4(c)), it appears that this area is in fact declining gradually.

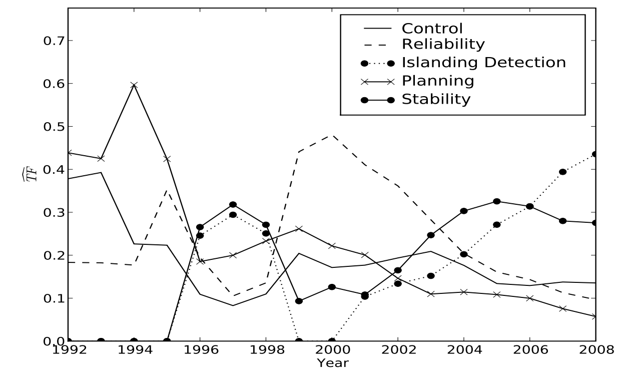
Batch 2 - {Power Quality, Electricity Markets/Economics, Protection, Forecasting, Micro-Grids/Smart Grids} (Fig. 5)



(a) Unnormalized

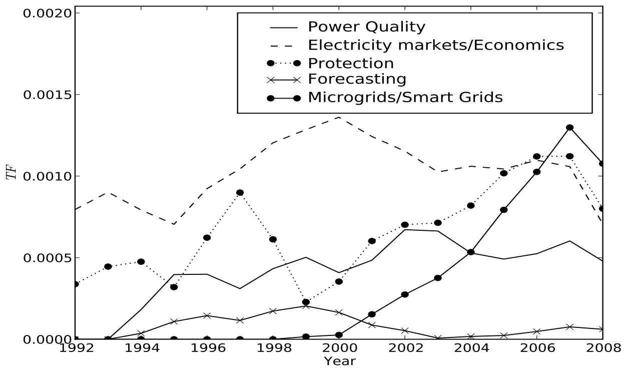


(b) Topic-wise normalization

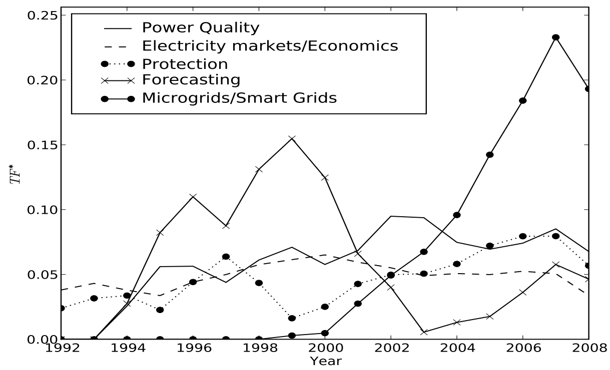


(c) Topic-wise & cross-sectional normalization

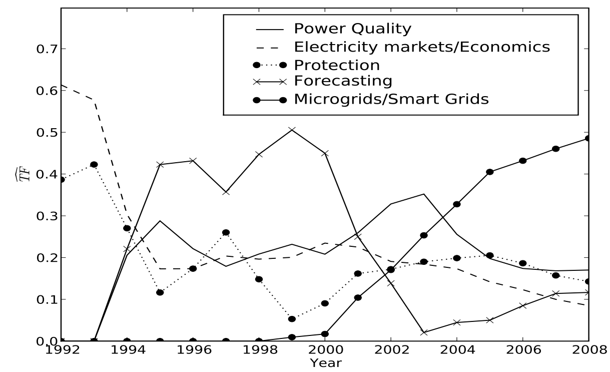
Figure 4: General studies (batch 1)



(a) Unnormalized



(b) Topic-wise normalization



(c) Topic-wise & cross-sectional normalization

Figure 5: General studies (batch 2)

1. The most prominent trend in this second batch of topics was for "micro-grids/smart grids", which in all three figures can be seen to be increasing rapidly post-2000.
2. Also, both "Power Quality" and "Protection" gradually increase in popularity throughout the analysis period. The term frequencies for "forecasting" can also be observed to be increasing in the initial period, however, after around the year 2000, they start to drop for around 3 years before staging a moderate "rebound" over the remaining years (though never quite regaining the initial highs).
3. "Electricity markets/economics" is another topic with inconsistent results - in Figs. 5(a) and 5(b), a mixed trend is observed though broadly speaking the popularity of this topic is seen to have increased on average. However, in contrast, the $\widehat{TF}$ plot (Fig. 5(c)) appears to show that activity in this topic is on the decline.

3.4. Cross-dimensional analysis

As mentioned in Section 2, we would also like to analyse the data using a "slice and dice" approach involving the topics in dimensions 2 and 3. For each of the "general studies" topics, we are interested in the relative growth potential of each topic for the different interface technologies:{Inverter,Synchronous,Induction}.

However, as occurences of each of these terms would be very low given the extremely specific conditions, the TF terms for each of the topic combinations would be averaged over the ranges [1992,2000] and [2000,2008] (inclusive). As an indicator of the growth potential for each combination, we simply use the differences between the mean TF for each of these two periods. These results are presented in Table 1.

Rank	Interface / Topic	$TF_{[1992,2000]}$ - $TF_{[2000,2008]}$			
		Inverter	Synchronous	Induction	Mean
1	Micro/Smartgrids	$\mathbf{2.9 \times 10^{-3}}$	2.8×10^{-4}	1.1×10^{-5}	1.1×10^{-3}
2	Power Quality	$\mathbf{2.2 \times 10^{-3}}$	3.6×10^{-4}	2.8×10^{-4}	9.4×10^{-4}
3	Islanding Detection	$\mathbf{1.8 \times 10^{-3}}$	4.4×10^{-4}	0.0	7.4×10^{-4}
4	Stability	7.1×10^{-5}	8.3×10^{-4}	$\mathbf{1.1 \times 10^{-3}}$	6.8×10^{-4}
5	Control	$\mathbf{1.5 \times 10^{-3}}$	3.4×10^{-4}	1.4×10^{-4}	6.8×10^{-4}
6	Reliability	$\mathbf{6.7 \times 10^{-4}}$	2.6×10^{-4}	7.9×10^{-5}	3.3×10^{-4}
7	Planning	1.4×10^{-4}	$\mathbf{1.7 \times 10^{-4}}$	$\mathbf{1.7 \times 10^{-4}}$	1.6×10^{-4}
8	Forecasting	0.0	5.4×10^{-5}	$\mathbf{4.2 \times 10^{-4}}$	1.6×10^{-4}
9	Electricity markets/Economics	$\mathbf{1.5 \times 10^{-4}}$	1.2×10^{-4}	0.0	9.2×10^{-5}
10	Protection	$\mathbf{3.0 \times 10^{-4}}$	2.2×10^{-5}	-2.4×10^{-4}	2.5×10^{-5}

Table 1: Growth rates for interface technologies w.r.t. each of general studies topics. The highest growth rate per row is printed in bold, and the rows are sorted in order of descending average growth rate.

The most prominent observation from this table was that for 7 out of the 10 topics, the inverter based interface technology had the highest rate of growth. Conversely, induction based interface technologies had the lowest growth rate for those 7 topics. However, it had the *highest* growth rate for the remaining three topics (stability, planning and forecasting), though in the case of planning, it had the same growth rate as for synchronous technologies.

3.5. Publication statistics by country and journals

Overall statistics				Papers published after 2006			
Country	No. papers	Population (millions)	No. papers /population	Country	No. papers	Population (millions)	No. papers /population
USA	1572	306	5.1	USA	400	306	1.3
United Kingdom	639	62	10.3	China	308	1336	0.2
China	574	1336	0.4	United Kingdom	215	62	3.5
Japan	323	128	2.5	Canada	142	34	4.2
Italy	315	60	5.2	Italy	119	60	2.0
Canada	298	34	8.8	Japan	118	128	0.9
Germany	264	82	3.2	India	99	1161	0.1
France	203	65	3.1	Spain	96	46	2.1
Spain	199	46	4.3	Germany	90	82	1.1
India	185	1161	0.2	Iran	75	70	1.1
Netherlands	150	16	9.4	France	64	65	1.0
Brazil	130	191	0.7	Netherlands	52	16	3.2
Australia	128	22	5.8	South Korea	51	48	1.1
South Korea	125	48	2.6	Brazil	49	191	0.3
Iran	122	70	1.7	Belgium	45	11	4.1

Table 2: Prolific countries

Rank (Weighted)	Journal	No. papers	No. citations	No. citations/ No. papers
1 (1)	IEEE Transactions on Power Systems	93	1132	12
2 (3)	IEEE Transactions on Power Delivery	68	478	7
3 (5)	Electric Power Systems Research	47	247	5
4 (9)	Dianli Xitong Zidonghua/Automation of Electric Power Systems	43	168	3
5 (4)	Energy Policy	37	275	7
6 (6)	IEEE Transactions on Energy Conversion	37	235	6
7 (2)	IEEE Transactions on Power Electronics	32	610	19
8 (7)	Journal of Power Sources	28	234	8
9 (15)	BWK - Energie-Fachmagazin	28	3	0
10 (12)	Renewable Energy	23	72	3
11 (8)	IEEE Transactions on Industry Applications	23	176	7
12 (10)	IET Generation, Transmission and Distribution	22	159	7
13 (11)	Energy	17	88	5
14 (14)	IEEJ Transactions on Power and Energy	17	11	0
15 (13)	International Journal of Electrical Power and Energy Systems	16	37	2

Table 3: Top-fifteen journals (by No. papers). Ranks in brackets are based on the number of incoming citations

Rank (Weighted)	Journal	No. papers	No. citations	No. citations/ No. papers
1 (2)	Electric Power Systems Research	37	46	1
2 (9)	IEEE Transactions on Power Delivery	35	26	0
3 (1)	IEEE Transactions on Power Systems	34	55	1
4 (4)	Dianli Xitong Zidonghua/Automation of Electric Power Systems	28	32	1
5 (5)	IEEE Transactions on Energy Conversion	20	32	1
6 (6)	Energy Policy	16	29	1
7 (8)	IEEE Transactions on Power Electronics	14	27	1
8 (15)	Transactions of the Korean Institute of Electrical Engineers	12	0	0
9 (13)	Zhongguo Dianji Gongcheng Xuebao/Proc. Chinese Soc. of Electr. Eng.	10	2	0
10 (11)	IET Renewable Power Generation	10	9	0
11 (10)	Journal of Power Sources	9	14	1
12 (3)	IEEE Transactions on Industrial Electronics	9	37	4
13 (7)	Energy	9	28	3
14 (12)	IET Generation, Transmission and Distribution	9	3	0
15 (14)	Electric Power Components and Systems	9	1	0

Table 4: Top-fifteen journals w.r.t. papers published after 2006. Ranks in brackets are based on the number of incoming citations

In addition to the previous set of searches, we also generated publication counts according to the country of origin and journal. These statistics are presented in tables 2 (organized by country), 3 (by journal) and 4 (by journal, for papers published after 2006).

The distribution of publications by country of affiliation is presented in table 2; this table is divided into two halves - the first provides statistics which take all the papers into account, while the second half only takes "recent" (defined as the last three years) publications into account. The main observations were:

1. As expected the USA had the largest share of the publications. However, its lead over the other countries has been reduced in recent years; while the total number of papers published in the USA is around 2.5 times the number published by it's closest competitor, the ratio for the last three years has reduced to slightly under 1.5 times.
2. Overall, the UK has been ranked second in this list. However, while it appeard to have gained slightly on the USA in the last few years, the largest shift has been in papers published by Chinese researchers - not only has China moved up to second position, the ratio of Chinese to American papers has increased tremendously from around a third to almost three quarters.
3. Besides China, other developing countries also appear to have increased their research output, notably India (from 10th to 7th place), Iran (15th to 10th place).
4. From amongst the developed countries, Canada has made the greatest gains, moving from 6th to 4th place. However, Germany and France suffered significant declines from 7th and 8th to 9th and 11th positions respectively while Australia dropped off the top-fifteen list entirely.
5. In terms of publication density (the ratio of number of papers to population), the UK had the highest overall number, followed by the Netherlands and Canada. However, for the last three years, Canada had the largest publication density, while the UK and Netherlands had dropped to 3nd

and 4th position respectively. Belgium, a "newcomer" in the top-fifteen list, now occupied the 2nd position.

Statistics on the distribution of publications by journal titles have also been divided into general and recent tranches which have been divided into two tables, 3 and 4. Our observations are:

1. The top journal for DG-related research appears to be the IEEE Transactions on Power Systems; overall it had the largest number of relevant papers as well as the largest number of incoming citations. However, when only papers published after 2006 were considered, it was ranked third in terms of number of papers published, but still had the largest number of incoming citations.
2. Besides the above, the list had a large number of other IEEE Transactions. For both lists five of the top fifteen journals were IEEE Transactions.
3. One surprising observation that was partially addressed was that the journals IET Generation, Transmission and Distribution, IET Renewable Power Generation and IET Power Electronics, which are extremely prominent in the DG field, were initially missing from the overall list of prolific journals. However, upon closer inspection, it turned out that this was because both IET Renewable Power Generation and IET Power Electronics are new journals which have only appeared in the last two or three years, and as such would not fare well in a ranking based on total number of papers (in fact, it was this observation which originally motivated us to compile a set of tables which only considered papers published after 2006). In the table using recent papers, we see that IET Renewable Power Generation has appeared in the top-15 list, however, IET Power Electronics is still off the list - subsequent checks to Scopus' source list confirmed that this journal had yet to be added to their database. For IET Generation, Transmission and Distribution, it was noted that the journals title had previously been "IEE Proceedings on Generation, Transmission and Distribution", which had caused papers from the journal to be allo-

cated to different bins, thus diluting their impact. When the two titles are combined, we find that this journal has also moved into the list of top-15 titles. These are good examples of the limitations of the proposed method - i.e. that results are only as good as the data extracted from the source database, and is a motivating factor for combining query results from more than one database.

4. Another interesting development is the emergence of a number of Asian journals - Dianli Xitong Zidonghua and Zhongguo Dianji Gongcheng Xuebao from China, and the Transactions of the Korean Institute of Electrical Engineers. In the overall data, only Dianli Xitong Zidonghua is in the top-15 list but in the list which reflect recent publication trends we find that the other two have appeared in positions 8 and 9, respectively.
   However, upon more careful inspection, we find that the majority of the incoming citations for the first two journals originate from within the same journal, while for the Transactions of the Korean Institute of Electrical Engineers, there are no incoming citations at all. It would hence appear that, while the volume of research published in these journals is certainly increasing, the impact of this research is still relatively low, or is restricted to the respective local contexts.

4. Analysis

In the previous section, the results of the bibliometric analysis were presented, and broad trends and patterns described. In this section a more detailed discussion will be presented, and attempts will be made to link prominent observations to relevant developments in the DG domain.

By referring to Fig. 2 and Fig. 3, it can be seen that Fuel cells and inverter tend to follow the same trend. The strong correlation between both topics id due to the factthat inverters are the sole interface option for fuel cells. During earlier years, PV was the most dominant research topic but the other technologies starting to attract more attention the late 90s (refer to Fig. 2). With regards to the type of interface, induction and synchronous were overall the main focus in the early 90s but with new emerging technologies, relying mainly on inverters, inverters have become in recent years of major research focus (refer to Fig. 3). In addition, the topics wind and induction share to some extent the same research trend which is obvious since the majority of wind turbines are connected to the power system through induction machines.

The research trend on the various research challenges associated with the different types of technologies and interfaces is given in Fig. 4 and Fig. 5. It can be seen that since 2002, the majority of research studies are of equal importance. One unique trend is the Smart Grid research trend which has been increasing since 1998. The increasing interest in smart grids is as a result of the increasing advancements in communications coupled with the increasing penetration of distributed generation in power systems. Consequently, the IEEE launched in 2009 a new transaction IEEE Transactions on Smart Grids that will address and focus on research advancements in this area. Recently, most of the research studies, given in Fig. 4 and Fig. 5, tend to be of equal importance except for islanding detection and stability which have a higher term frequency factor. As a result, the IEEE launched in 2009 another transaction IEEE Transactions on Sustainable Energy which will include evaluation of power systems that are affected by sustainable energy.

As highlighted earlier, DG could be interfaced to the distribution system through an inverter, synchronous or induction machine. From Table 1, it can be seen that most of the interface topics are of relative importance for inverter based and induction based DG. This could be related to the fact that an inverter interface is the best candidate for DG sources that inherently generate DC such as PV and Fuel cells. On the other hand, while existing wind turbine systems can use either synchronous or induction interfaces, the induction machine interface has several advantages which include lower capital cost, lower maintenance cost as well as better transient performance. For this reason, the induction machine interface is widely and extensively used for wind turbines [35]. For brevity, we will focus our discussion of some of the topics presented in Table I.

The main role of an inverter is to convert the DC power generated by the

DG source to AC power necessary for feeding loads. Inverters are composed of a group of switches that are controlled in such a way to synthesize the DC waveform into an AC waveform. In this conversion process, harmonics are generated which results in power quality problems [36]. Synchronous and induction machines generally do not suffer from this problem and for this reason power quality is considered one of the main challenges when designing inverter based DG (refer to Table I). The second challenge that is of relative importance is islanding detection. Islanding is a condition where the DG is operating in an isolated mode and not directly connected to the utility. The IEEE Standards necessitate the disconnection of a DG once it is islanded to avoid any power quality and safety problems[1]. This topic is a major challenge when implementing inverter and synchronous based DG because both types can sustain stable operation in the absence of the grid connection. On the other hand, induction machines require a grid connection for stable operation and for this reason an islanding condition could be easily detected and a sophisticated islanding detection method is not required [29]. This coincides with the results presented in Table I where most of the research work for islanding detection falls under the inverter and synchronous interface area.

Forecasting, stability and planning are three research topics where induction based DG become more dominant. Induction based DG are commonly used for wind generation. Large scale wind installation commonly referred to as wind farms are usually connected on the transmission and sub-transmission levels and their capacity is in the range of a common generation plant. Accurate forecasting techniques and stability analysis becomes an essential requirement to guarantee efficient, reliable and stable power system operation. Taking into account wind generation in planning studies is a result of the increasing reliance on and penetration of wind generation.

Two research topics that have been drawing much attention recently are micro-grids and smart grids. DG can form a new type of power system, the

[1]IEEE Std. 1547-2003

so-called micro-grid. Micro-Grids can be viewed as a group of DG sources operating either connected or isolated to/from the main grid [37, 38]. Smart grids are an extension of the micro-grid concept. Smart grid is a distribution grid with a communication infrastructure with capability to control the different components within the smart grid to achieve efficient, reliable and secure operation [22, 23]. For utilities with high penetration of DG sources, the practice of disconnecting all DG during a grid failure is neither practical nor reliable. There is a pressing need for modifications to these policies with regard to DG disconnection after a disturbance. The current IEEE standards do not address the topic of micro-grids. However, a new IEEE standard is currently being developed to address micro-grids [39]. Inverter based DG provides an attractive option due to its fast transient response and flexibility in interface control design. For this reason, inverter based DG are the most dominant technology for implementing smart grids and microgrids.

5. Conclusions

Below we summarize the main findings, discuss limitations of the current analysis, and offer suggestions for future research in the area of bibliometric analysis of DG research.

5.1. Results

The results presented in this paper demonstrate that the proposed methodology, which is based on a bibliometric approach, is capable of extracting valuable information from semi-structured sources of data. While this study is still preliminary, this information is already useful in helping to improve our understanding about trends and patterns in research, and would already be of great interest to a researcher in the field of DG. As has been discussed in sections 3 and 4, the trends highlighted by the bibliometric analysis certainly appear to be in agreement with developments in the field of DG, and could support the formulation of well informed and effective research policies. Some recommendations are:

1. Smart grids and micro-grids are considered amongst the hottest research topics in the field of DG. This is also evident from the increasing number of conferences that have panels focusing on this topic.
2. Among all DG interface types, inverter based DG seems to be the dominant type with many interesting and challenging problems.
3. Topics such as protection and stability in distributed system design are now becoming of major importance due to the high penetration of DG.

5.2. Methods

As with any computational framework which exploits semi-structured data, there were some issues which need to be highlighted. Firstly, it is important to note that success in using this approach to analyse research progress is contingent upon our ability to correctly identify publications which are relevant to the topics of interest. So, for example, the frequency of the term "wind" is used to estimate the level of activity in wind power research. While this successfully identifies many relevant papers, there will certainly be occurrences of false positives or negatives; i.e. there might be publications with abstracts containing the word "wind", but which are not directly relevant to wind power. Conversely, there might be publications which are in fact relevant to wind power, but which have abstracts which do not explicitly mention the word "wind".

A further problem is with inconsistent database capabilities. To access a larger body of documents, an obvious measure would be to submit queries to a number of different academic search engines (for example, the "Scirus" search engine, or Google's Scholar search engine), or to conduct full text searches of these publications. Unfortunately, many search engines do not allow full-text searches, or exporting of search results for use in bibliometric analysis.

To help counter these problems and to increase the quality and applicability of this approach, we propose the following avenues for future work:

1. **Intelligent feature extraction** - A variety of techniques from the machine learning and semantic technology communities could be brought to

bear. In particular, it would be interesting to see the value of incorporating semantically-enabled features into the search process - i.e. instead of using manually generated keyword searches, computational techniques could be used to group together terms which are either synonymous, or which are observed to co-occur frequently, and to combine these terms appropriately when conducting the searches.

2. **Information fusion** from multiple, heterogeneous data sources - as noted above, different databases provide different capabilities, and cover different subsets of the academic literature. Instead of accessing individual databases in isolation, information extracted from different sources could be combined, and in a way which allows for the heterogeneity. So for example, a weighting mechanism could be devised to allow results of full-text searches from one database to be combined with a title-only search from another.

3. **Tools development** - thus far the analysis has been carried out using a collection of python scripts. While these have been very useful for our purposes, we plan to make these methods useable for a broader audience by creating a set of user-friendly software applications. These tools will incorporate the functionality of the scripts but in an intuitive and accessible way.

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