A Detailed Bibliographic Analysis of Optimal PMU Placement Problem in Conventional Power Systems and in Smart Grids

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***Abstract*—This paper presents a detailed bibliographic analysis of papers concerning the optimal PMU placement (OPP) problem that have more than ten citations and sorted in descending order by the number of citations. The results from this analysis show that IEEE journal and IEEE conference papers are the most influential. The most productive and high-impact authors, institutions, and countries/regions are also identified. According to this analysis, U.S.A. researchers and institutions dominate the research on OPP problem, whereas the most productive and influential authors are A. Abur and B. Gou. Moreover, Texas A&M University, Virginia Polytechnic Institute & State University, and University of Cyprus are the three most productive and influential institutions in OPP research.**

***Index Terms*—Bibliographic analysis, impact, optimal PMU placement, phasor measurement unit (PMU), productivity, smart grid.**

I. Introduction

THE existing power systems as well as the smart grids utilize a number of advanced computing, networking and measurement technologies. One of those new technologies is an accurate and reliable measurement device known as Phasor Measurement Unit (PMU) [1]. As the availability of PMUs at substations is increased, the performance of different essential functions, concerning the monitoring, protection, and control of grids, is improved [2]. Due to the relatively high cost of these devices, an important issue of power engineering is their optimal placement in order to render an observable grid. This is known as *optimal PMU placement* (OPP) problem. Several conventional, heuristic and metaheuristic optimization techniques have been proposed to solve the OPP problem [31]. Taxonomy of OPP methodologies, offering a unifying description of 38 selected state-of-the-art OPP works, can be found in [31]. On the other hand, this paper makes a detailed bibliographic analysis of 81 selected OPP works, which satisfy the criterion each work to have more than ten citations. Consequently, power system engineers and researchers can found in this paper and in [31] a thorough mapping and description, respectively, of the state-of-the-art OPP works.

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More specifically, in this paper, a bibliographic analysis is employed to assess the publication and citation patterns of journal articles and conference papers of the OPP literature, in terms of the most influential journals and conferences as well as the most productive and highest-impact authors, institutions, and regions in worldwide OPP research. Section II describes the bibliographic analysis methodology, and Section III presents the findings from this analysis. Section IV concludes the paper.

II. Bibliographic Analysis Methodology

For the purposes of this analysis the metadata for publications from IEEE Xplore and other digital libraries was downloaded. The downloaded metadata includes information about the title, abstract, authors, author affiliations, references, and keywords. This research considers journal articles and conference papers having more than ten citations and concerning the OPP problem. In order to quantify and estimate the impact of these papers, the Google Advanced Scholar Search was used to download citation information during September 2014.

In the first stage, the bibliographic references are classified as either journal articles or conference papers and divided in categories by pre-processing the identity of journals and conferences. In a next stage, the data collection focuses mainly on authors' identification, pre-processing their full names and affiliations and making an effort to align authors with multiple affiliations so that their contributions would not be underestimated. Moreover, in case of institutions and countries/regions, the multiple affiliations were considered independently.

The productivity of authors, institutions, and countries/regions is estimated by using a productivity index known as adjusted productivity score (APS) [3], [4].

We define by N the number of papers of an author, n_i the number of authors of the *ith* paper, and c_i the number of citations of the *ith* paper. Assuming that a paper receives a credit equal to one, the APS of an author is defined as the sum of credits of all his/her publications:

$$APS = \sum_{i=1}^{N} \frac{1}{n_i} \tag{1}$$

The impact of individual authors, institutions, and countries/regions is studied based on the adjusted citation score (ACS). The ACS of an author is defined as the sum of citation credits of all his/her publications [4], [5]:

$$ACS = \sum_{i=1}^{N} \frac{c_i}{n_i} \quad (2)$$

The total count of papers is also calculated for each author, institution and country/region, respectively.

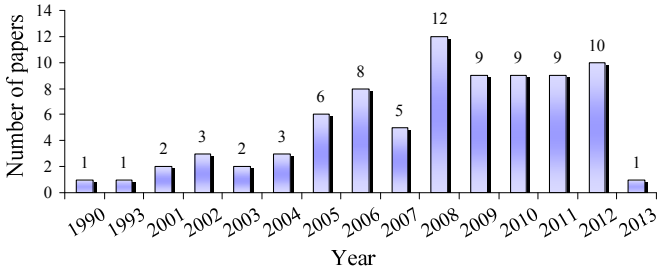
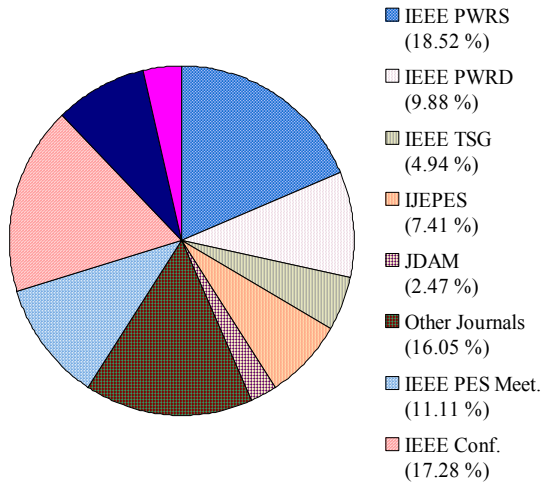


Fig. 1. Total number of papers per year dealing with the solution of OPP having more than ten citations in September 2014.



IEEE PWRS:	*IEEE Transactions on Power Systems*
IEEE PWRD:	*IEEE Transactions on Power Delivery*
IEEE TSG:	*IEEE Transactions on Smart Grid*
IJEPES:	*International Journal of Electrical Power & Energy Systems*
JDAM:	*International Journal of Discrete Applied Mathematics*
Other Journ.:	The rest journals of bibliography
IEEE PES Meet.:	*IEEE PES Winter, Summer and General Meetings*
IEEE Conf.:	*IEEE Conferences*
Conf. spons. by IEEE:	Conferences sponsored by IEEE
Other Conf.:	The rest conferences of bibliography

Fig. 2. Papers' distribution per journal and conference.

III. Bibliographic Analysis Results

A. Selection Criterion

In order an OPP work to be included in this bibliographic analysis, it should have more than ten citations.

B. Total Number of Selected Papers, Authors, Institutions, and Countries/Regions

During the period between 1990 and September 2014, a total of 81 papers with more than ten citations, dealing with the solution of the OPP problem, have been published in journals and conferences [6]−[86]. In these 81 papers, listed in Section V and sorted in descending order by the number of citations, 181 authors from 80 institutions in 21 countries/regions were identified. Fig. 1 shows the total number of OPP papers per year having more than ten citations in September 2014.

TABLE I
Most Productive Authors Sorted by APS

Rank	Name	Affiliation	Counts	APS
1	A. Abur	Texas A&M Univ.; Northeastern Univ. of Boston, USA	8	3.67
2	S. Chakrabarti	Univ. of Cyprus, Cyprus; Queensland U of Tech., Australia	6	2.00
3	E. Kyriakides	Univ. of Cyprus, Cyprus	6	2.00
4	B. Gou	Energy Systems Research Center at Univ. of Texas at Arlington, USA	2	2.00
5	B. Mohammadi-Ivatloo	Sharif Univ. of Technology, Tehran, Iran	2	1.50
6	A. Aazami	Univ. of Waterloo, Canada	2	1.50
7	A. G. Phadke	Virginia Polytechnic Inst. and State Univ., USA	4	1.42
8	R. Emami	Northeastern Univ. of Boston, USA	3	1.33
9	R. Kavasseri	North Dakota State University, USA	3	1.33
10	R. F. Nuqui	ABB US Corporate Research Center, Raleigh, USA; Virginia Polytechnic Inst. and State Univ., Blacksburg, USA	3	1.25

TABLE II
Most Productive Institutions Sorted by Counts

Rank	Institution	Counts
1	Sharif University of Technology, Iran	7
2	University of Cyprus, Nicosia, Cyprus	6
2	Virginia Polytech. Inst. & State Univers., USA	6
4	Northeastern University, Boston, USA	5
4	Texas A&M University, College Station, USA	5
6	North Dakota State University, Fargo, USA	3
6	Illinois Institute of Technology, Chicago, USA	3
6	Indian Institute of Technology, Kanpur, India	3
9	East China Jiaotong University, Nanchang, China	2
9	Energy Systems Research Center, Univers. of Texas, USA	2
9	Hydro-Québec Research Institute/IREQ, Canada	2
9	National Technical University of Athens, Athens, Greece	2
9	North China Electric Power University, Beijing, China	2
9	Georgia Institute of Technology, Atlanta, USA	2
9	Zhejiang University, Hangzhou, China	2
9	RWTH Aachen University, Germany	2
9	University of Waterloo, Ontario, Canada	2
9	Princeton University, Princeton, USA	2
9	Carnegie Mellon University, Pittsburgh, USA	2
9	ABB US Corporate Research Center, Raleigh, USA	2
9	Electric Power Research Institute, Palo Alto, USA	2
9	"Politehnica" University of Bucharest, Romania	2
9	Queensland University of Technology, Australia	2

C. Classification per Journal Name and Conference Family

The 81 OPP publications, selected according to the criterion of having more than ten citations (Section III.A), are further classified as either journal articles or conference papers and divided into ten categories, as shown in Fig. 2. In IEEE Transactions on Power Systems, IEEE Transactions on Power Delivery and IEEE Transactions on Smart Grid, the 33.34% of total papers have been published, which corresponds to the 56.25% of total count of journal articles.

TABLE III
MOST PRODUCTIVE INSTITUTIONS SORTED BY APS

Rank	Institution	APS
1	Sharif University of Technology, Iran	4.17
2	Northeastern University, Boston, USA	4.00
3	University of Cyprus, Nicosia, Cyprus	3.83
3	Texas A&M University, USA	3.83
5	Virginia Polytech. Inst. & State University, USA	2.75
6	North Dakota State University, Fargo, USA	2.33
7	East China Jiaotong University, China	2.00
7	Energy Systems Research Center, Univers. of Texas, Arlington, USA	2.00
7	Hydro-Québec Research Institute/IREQ, Varennes, Canada	2.00
7	National Technical University of Athens (NTUA), Athens, Greece	2.00
7	North China Electric Power University, Beijing, China	2.00
7	Zejiang University, Hangzhou, China	2.00

It should be noted that in the rest of journals, other IEEE journals are also included, such as *IEEE Systems Journal* and *IEEE Transactions on Instrumentation and Measurement*, which means that the influence of IEEE journals on OPP problem research is even bigger. Similar results can be also obtained regarding IEEE conferences. Fig. 2 shows that 37.04% of total papers have been presented at *IEEE conferences* (including IEEE PES meetings, conferences organized by IEEE, and conferences sponsored by IEEE), which corresponds to the dominating percentage of 90.91% of the total number of conference papers.

D. Productivity Analysis

The most productive among the 181 authors who have been involved in OPP problem research are reported in Table I, sorted by APS. It can be seen that A. Abur, who was faculty member at Texas A&M University, College Station, until Nov. 2005, when he joined the faculty of Northeastern University, Boston, as a Professor and Chair of the Electrical and Computer Engineering Department, is the author with the highest APS and the most publications in OPP. The second most productive authors are E. Kyriakides, who is faculty member at the University of Cyprus and S. Chakrabrati who was with the University of Cyprus and Queensland University of Technology until Nov. 2009 and with Indian Institute of Technology, Kanpur, from Dec. 2009 to present. Lots of the top authors work with collaborators and are involved in more than three papers with an adjusted productivity score of equal or more than 1.20.

Table I shows that among the top ranked authors, six of them are in USA and the rest in Australia, Cyprus, Iran and Canada. The ten leading institutions in a list of 80 institutions that have been involved in OPP problem research, based on paper counts, are provided in Table II. It can be seen that the five most productive institutions have published more than four articles. The flagship in the productivity list is the Sharif University of Technology, Tehran, followed by the the University of Cyprus, Nicosia; the Virginia Polytechnic Institute & State University; the Northeastern University of Boston and the Texas A&M University, College Station.

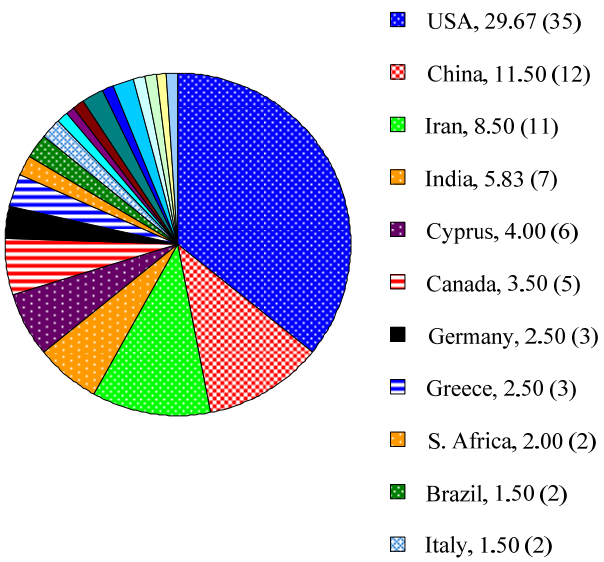


Fig. 3. Productivity and impact per country/region by APS and paper counts.

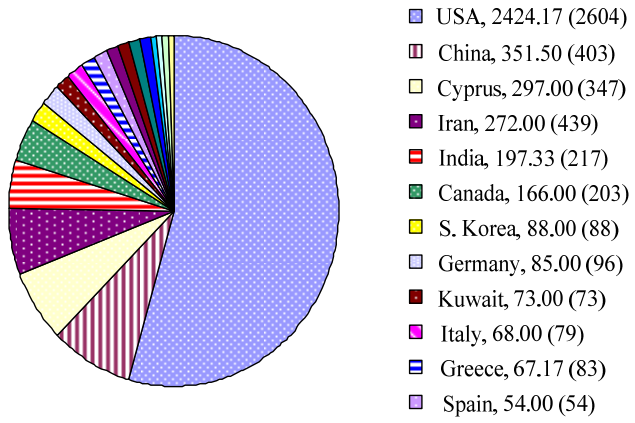


Fig. 4. Productivity and impact per country/region by ACS and citation counts.

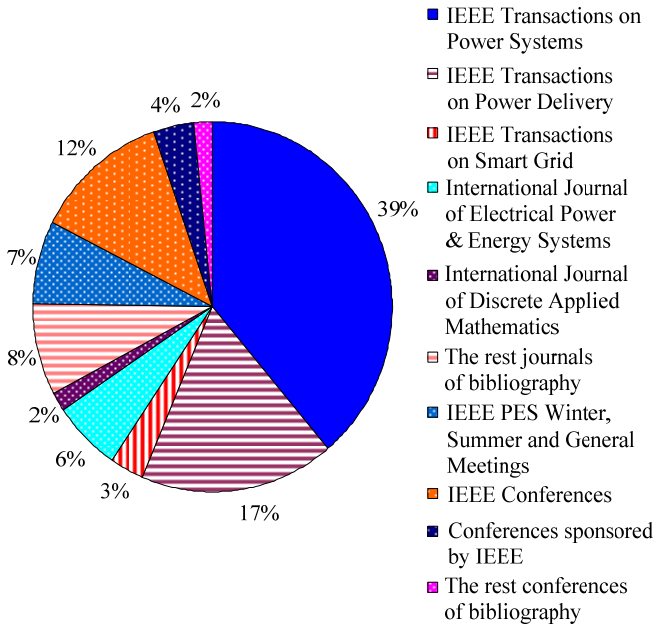


Fig. 5. Percentage of citations per journal and conference.

TABLE IV
MOST CITED PAPERS

Rank	Title	Authors	Year	Ctry / Reg	Cites
1	Power system observability with minimal phasor measurement placement	T. L. Baldwin, L. Mili, M. B. Boisen Jr., R. Adapa	1993	USA	468
2	Observability analysis and measurement placement for systems with PMUs	B. Xu, A. Abur	2004	USA	260
3	Phasor measurement unit placement techniques for complete and incomplete observability	R. F. Nuqui, A. G. Phadke	2005	USA	251
3	Nondominated sorting genetic algorithm for optimal phasor measurement placement	B. Milosevic, M. Begovic	2003	USA	211
5	Placement of PMUs to enable bad data detection in state estimation	J. Chen, A. Abur	2006	USA	163
6	Optimal placement of phasor measurement units for power system observability	S. Chakrabarti, E. Kyriakides	2008	Cyprus	155
7	Generalized integer linear programming formulation for optimal PMU placement	B. Gou	2008	USA	141
8	A distributed state estimator utilizing synchronized phasor measurements	W. Jiang, V. Vittal, G. T. Heydt	2007	USA	110
9	Optimal PMU placement for full network observability using Tabu search algorithm	J. Peng, Y. Sun, H. F. Wang	2006	China, UK	103
9	Placement of synchronized measurements for power system observability	S. Chakrabarti, E. Kyriakides, D. G. Eliades	2009	Cyprus	103

TABLE V
MOST CITED AUTHORS (TOP TEN)

Rank	Name	Institution	Cites	ACS
1	A. Abur	Texas A&M Univ., College Station; Northeastern U, Boston	639	308.00
2	B. Gou	Energy Systems Research Center at Univ. of Texas at Arlington	224	224.00
3	A. G. Phadke	Virginia Polytechnic Inst. and State Univ., Blacksburg	353	158.08
4	R. F. Nuqui	ABB US Corporate Research Center, Raleigh; Virginia Polytechnic Inst. and State Univ., Blacksburg	329	153.75
5	B. Xu	Texas A&M Univ., College Station	314	148.00
6	S. Chakrabarti	Univ. of Cyprus, Nicosia; Queensland U of Tech.	347	138.92
6	E. Kyriakides	Univ. of Cyprus, Nicosia	347	138.92
8	R. Adapa	Electric Power Research Inst. (EPRI), Palo Alto	511	131.33
8	T. Baldwin	Virginia Polytechnic Inst. and State Univ., Blacksburg	511	131.33
8	L. Mili	Virginia Polytechnic Inst. and State Univ., Blacksburg	511	131.33

TABLE VI
MOST CITED INSTITUTIONS (TOP TEN)

Rank	Title	Ctry/Reg	Cites	ACS
1	Texas A&M Univ., College Station	USA	540	442.50
2	Virginia Polytechnic Inst. and State Univ., Blacksburg	USA	821	404.50
3	Univ. of Cyprus	Cyprus	347	297.00
4	Electric Power Research Inst. (EPRI), Palo Alto	USA	511	255.50
5	Energy Systems Research Center (ESRC), Univ. of Texas, Arlington	USA	224	224.00
6	Georgia Inst. of Tech., Atlanta	USA	232	221.50
7	Northeastern Univ., Boston	USA	286	197.00
8	Sharif Univ. of Technology, Tehran	Iran	313	152.33
9	ABB US Corporate Research Center, Raleigh	USA	286	143.00
10	Hydro-Québec Research Inst. (IREQ), Varennes	Canada	114	114.00

Table III shows the institutions ranking based on APS. Fig. 3 shows the high-productivity countries in bibliography. Among the 21 countries/regions with OPP publications, the most productive country is the USA, followed by China and Iran. The numbers in the legend of Fig. 4 represent the adjusted productivity score and the counts of each country, respectively.

E. Impact Analysis

The 81 papers of OPP research with more than ten citations are cited 4442 times, which means that on average each of these papers is cited 54.84 times.

The list of most frequently cited journals and conferences includes the *IEEE Transactions on Power Systems*, the *IEEE Transactions on Power Delivery*, the *IEEE Conferences*, and the *IEEE PES Meetings (Winter, Summer, General),* with 1733, 767, 538, and 319 cites, respectively. The percentage of citations for each group of journal articles and conference papers is shown in Fig. 5.

The ten most frequently cited papers are shown in Table IV. The most cited paper is a pioneering proposal on OPP problem by T. L. Baldwin *et al*. Seven of the high-impact papers are from the USA, whereas the others are from Cyprus, and collaboration between UK and China. The ten most frequently cited authors in a list of 181 cited authors and the ten most often cited institutions in a list of 80 cited institutions are reported in Tables V and VI, respectively.

Due to their high rank presence in both Tables I and V, A. Abur and B. Gou are the authors with the highest productivity score and impact among the listed authors. Tables II, III and VI show that Texas A&M University, Virginia Polytechnic Institute & State University, and University of Cyprus, are the three most dominant and highest impact institutions supporting the OPP research.

Fig. 4 shows the high-impact countries in bibliography. The numbers in the legend of Fig. 4 represent the adjusted citation score and the counts of each country, respectively. The cited papers represent 21 countries/regions and the country with the most cited papers is USA, followed by China and Cyprus.

IV. CONCLUSIONS

This paper has analyzed the state of the OPP problem research based on the publications in journals and conferences. According to this research, USA researchers and institutions dominate the OPP problem bibliography.

The second most productive countries are China and Iran. A. Abur and B. Gou are the most productive and highly influential authors, whereas Texas A&M University, Virginia Polytechnic Institute & State University, and University of Cyprus, are the three institutions presenting the highest productivity and the most highly cited research, whereas the Sharif University of Technology, Tehran, is the most productive institution. The top three journals with the most OPP publications are the *IEEE Transactions on Power Systems*, the *IEEE Transactions on Power Delivery*, and the *International Journal of Electrical Power & Energy Systems*. The high-impact conferences are the IEEE PES meetings (Winter, Summer and General), the IEEE conferences and the conferences sponsored by IEEE.

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