The State of the Art in Smart Grid Domain: A Network Modeling Approach

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Abstract: Agent-based computing and multi-agent systems are important tools in the domain of smart grid. Various properties of agents like self-organization, co-operation, autonomous behavior, and many others allow researchers to well represent the smart grid applications and models. From past few decades, various research attempts have been made in the smart grid domain by adopting the agent-based computing technology. The research publications are growing in number which makes it difficult to locate and identify the dynamics and trends in the research. Scientometric analysis is a useful tool to perform a comprehensive bibliographic review. It allows not only to understand the key areas of research but also provide visual representation of each entity involve in the research. In this study, we provide a detailed statistical as well as visual analysis of agent-based smart grid research by adopting complex network-based analytical approach. The study covers all scientific literature available online in Web of Science database. We are interested in identification of key papers, authors, and journals. Furthermore, we also investigate core countries, institutions, and categories.

Keywords: smart grid; multi-agent systems; network modelling; scientometric analysis.

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Introduction

From past few decades, agent-based computing has received a great deal of attentions in the smart grid domain. The agents have various behaviors like atomicity, communication, self-organization, co-operation etc. By developing agent-based models, one can easily represent any complex adaptive systems where the agent's features are main concerns.

In scientific literature, a number of studies have been done on the smart grid by making use of agent-based computing technology. Some of the key examples are as following. For example it is applied for demand response in (Kim, Zhang, Van Der Schaar, & Lee, 2016; Siebert, Sbicca, Aoki, & Lambert-Torres, 2017), smart home management (Dusparic, Harris, Marinescu, Cahill, & Clarke, 2013; G. Wang et al., 2017), electric vehicle charging and discharging (Golpayegani, Dusparic, Taylor, & Clarke, 2016; Jannati & Nazarpour, 2017; Yao, Lim, & Tsai, 2017). The agent-based smart grid systems can also be noted for appliance scheduling (Muralitharan, Sakthivel, & Shi, 2016), storage management (Ju et al., 2018; Lamedica, Teodori, Carbone, & Santini, 2015; Shirzeh, Naghdly, Ciufo, & Ros, 2015). These studies have shown the importance and utility of agent-based computing technology in the domain of smart grid.

One key problem in scientific literature is that the research is growing very fast. From different countries and organization researchers make their contribution in the smart grid domain. In literature of smart grid, there are also several surveys and reviews papers, which provide a detailed analysis of the domain, available techniques, and tools. Some of the examples of surveys can be seen in (Rehmani, Davy, Jennings, & Assi, 2019; Risteska Stojkoska & Trivodaliev, 2017; Siano, 2014). Although there are numerous surveys and reviews in the domain, there exist one key problem that researchers are unable to understand and locate trends and dynamic of the domain. Another problem with these surveys is that they are outdated and target a specific requirement of the study. These surveys are unable to cover all the published work.

A network modeling approach is a useful tool for bibliographic reviews. It allows not only the visual analysis but also a detailed statistical analysis of the domain. However, to the best of our knowledge, currently there exists no study on bibliographic analysis of the agent-based smart grid research.

In this paper, we provide a detailed survey of the smart grid domain from agent-based perspective. We cover all studies currently available in the
domain on Web of Science database. This study adopts the network modeling approach - an approach of cognitive agent-based computing framework. The approach allows developing a network model, thus allows better understanding the domain in the form of network. Our key focus is on the analysis of key papers, journals, authors. We are also interested in the analysis of core countries, institutions, and categories.

**Methodology**

**Data collection:**

The dataset was collected from the Thomson Reuters web of knowledge database in the period of 1992 to 2019. The input data was retrieved on 7 November 2019, by using extended topic search of smart grid domain from agent technology perspective. The following search key words were used in data collection.

- Agent-based modeling of smart grid
- Multi-agent systems in smart grid
- Modeling and simulation of smart grid

We performed bibliographic search in different web of science databases included SCI-Expanded, SSCI, and A&HCI. Our results included different documents types such as articles, reviews, letters, and other editorial materials published in English language. Each record includes full information as document titles, author names, abstracts, and cited references. Our dataset contains a total of 3884 records. By addition of cited references, a total of 36317 nodes were counted.

**Tools and method:**

In this paper, we have adopted CiteSpace- a scientometrics analysis tool (Chen, 2014, 2016). The tool allows visual analysis of the citation network. It uses different colors that highlight details information about nodes and links of the citation network. CiteSpace offers tools and techniques for developing various complex networks based on years, time slice, centrality, and clustering. The developed network can be analyzed and various details information can be collected about a research domain. For example, based on the extracted network, we can get information about core authors, documents, and journals. Additionally, we can also analyze the top country, institutions, and category of a specific research topic and domain.

The research method followed in our study is adapted from (M. A. K. Niazi, 2017). The methodology diagram is shown in Figure 1. First, we start by collecting bibliographic data of marketing domain from the web of science. For visual analysis, we use the CiteSpace network modeling tool.
Our analysis starts by developing network clusters. It is followed by an analysis of Journals in order to identify core Journals of Marketing domain. Our next research objective is to identify top articles, and most cited authors in marketing research studies. Additionally, our next focus is on the identification of core country, category, and institutions.

![Research method for bibliographic analysis of Marketing research](image)

**Figure 1:** Research method for bibliographic analysis of Marketing research adopted from (Farooq, Khan, Niazi, Leslie, & Hussain, 2018)

**Results**

We start with a basic look at the overall picture of bibliographic data retrieved from web of science. Figure 2 shows total publications by year. As we can see here, the use of agent technology in smart grid starts primarily in 2007. The research gradually was rising and in the period of 2015 to 2019 the research achieved a great attention from research community in the domain. In this period, more than 550 different research publications were observed.

![Total publications by year](image)

**Figure 2:** Total publications by year
(Authors analysis on collected data from WoS)
The popularity of any research domain is based on number of citation of documents. Thus, we also needed to observe the citation phenomena in the domain in order to get deep insights of the domain advancement. Figure 3 shows total citations by year in smart grid domain using agents’ technology. Here, we can see that the citation starts with a very small number and gradually rising to almost 1000 citations in the year of 2018.

![Figure 3: Total citations by year](Authors analysis on collected data from WoS)

1. Identification of the largest cluster

In this section, we present our first analysis to observe the big picture of the domain. In Figure 4 top clusters are displayed is a visual form. These clusters are formed using CiteSpace analysis tool. Each cluster is named based on index terms.

In agent-based smart grid research, researchers work on different aspects of the domain. Here, we can see that the hottest area of research is “demand response management in the smart grid”. Next, machine learning techniques and agent-based systems are adopted in the domain. These techniques are utilized to develop an energy efficient system. Other research topics are voltage regulations and electric vehicles management. The detailed analysis of the largest clusters is given in the following.

In Table 5, frequency-based document analysis is given. Here, we notice that the article (Mohsenian-Rad, Wong, Jatskevich, Schober, & Leon-Garcia, 2010) has the highest frequency among all cited articles. Next, (Fang, Misra, Xue, & Yang, 2012) is the most cited article in the domain. Following
by (Palensky & Dietrich, 2011), (Farhangi, 2010), (Gungor et al., 2013) and (Siano, 2014). These are top documents based on frequency in the smart grid domain.

The detailed summary of the top clusters can be found in
Table 1. Cluster #0 contains 80 nodes in the year 2011. The mean silhouette score of this cluster is 0.626 indicate high homogeneity in the cluster. Cluster #1 has 50 node and 0.861 silhouette score in 2009. The mutual terms of this cluster are electric vehicles, charging and discharging. Cluster #2 has 49 nodes with 0.807 silhouette score which indicates homogeneity in the cluster. The average year of this cluster is 2014. Cluster #3 has 42 nodes and 0.784 silhouette score in the year 2009. This cluster shares research mostly on power line communication. Cluster #4 has 40 nodes and 0.719 silhouette score which indicate the homogeneity in the cluster in the year 2010. The terms controllable and smart home are used in this cluster. The next top cluster contains 23 nodes along with 0.764 silhouette score. The average year of this cluster is 2008. Mostly papers in this cluster share noise reduction term.

Figure 4: Top clusters by index terms
(Authors analysis on collected data from WoS)
Table 1: Summary of top clusters
(Authors analysis on collected data from WoS)

| ClusterID | Size | Silhouette | mean(Year) | Label (LLR)                                                                 | Label (MI)                                                                 |
|-----------|------|------------|------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| 0         | 80   | 0.626      | 2011       | demand response, home energy management, smart energy hub, appliance         | distributed storage, scheduling problem, bacteria foraging optimization     |
|           |      |            |            | scheduling, demand-side management                                          |                                                                             |
| 1         | 50   | 0.861      | 2009       | electric vehicle, smart charging                                            | double control, ev group, coordinated charging and discharging              |
| 2         | 49   | 0.807      | 2014       | machine learning, power markets, smart contract                            | electric power network, accuracy, cybersecurity, incentive-based demand     |
|           |      |            |            |                                                                             | response                                                                    |
| 3         | 42   | 0.784      | 2009       | multi agent system, micro-grid                                             | power system automation, power line communication                           |
| 4         | 40   | 0.719      | 2010       | Zigbee, smart home grid                                                     | controllable load                                                           |
| 5         | 23   | 0.764      | 2008       | voltage regulators                                                         | Powerline, noise reduction                                                  |

Table 2: Top document based on citations
(Authors analysis on collected data from WoS)

| Citation counts | Reference                                                                 |
|-----------------|---------------------------------------------------------------------------|
| 164             | Mohsenian-rad AH, 2010, IEEE T SMART GRID, 1, 320                         |
| 118             | Fang X, 2012, IEEE COMMUN SURV TUT, 14, 944                               |
| 115             | Mohsenian-rad AH, 2010, IEEE T SMART GRID, 1, 120                         |
| 96              | Palensky P, 2011, IEEE T IND INFORM, 7, 381                               |
Table 3: Top document based on bursts
(Authors analysis on collected data from WoS)

| Bursts | References |
|--------|------------|
| 12.66  | Mcarthur SDJ, 2007, IEEE T POWER SYST, 22, 1743 |
| 12.44  | Dimeas AL, 2005, IEEE T POWER SYST, 20, 1447 |
| 11.68  | Siano P, 2014, RENEW SUST ENERG REV, 30, 461 |
| 10.46  | Olivares DE, 2014, IEEE T SMART GRID, 5, 1905 |
| 9.25   | Kempton W, 2005, J POWER SOURCES, 144, 268 |
| 9.05   | Deng RL, 2015, IEEE T IND INFORM, 11, 570 |
| 8.78   | Kempton W, 2005, J POWER SOURCES, 144, 280 |
| 8.38   | Vardakas JS, 2015, IEEE COMMUN SURV TUT, 17, 152 |
| 8.33   | Eddy YSF, 2015, IEEE T POWER SYST, 30, 24 |
| 8.26   | Albadi MH, 2008, ELECTR POW SYST RES, 78, 1989 |

Table 4: Top document based on centrality

| Centrality | References |
|------------|------------|
| 0.16       | Mohsenian-rad AH, 2010, IEEE T SMART GRID, 1, 320 |
| 0.12       | Pipattanasomporn M, 2009, POW SYST C EXP 2009, 0, 1 |
| 0.10       | Zimmerman RD, 2011, IEEE T POWER SYST, 26, 12 |
| 0.09       | Farhangi H, 2010, IEEE POWER ENERGY M, 8, 18 |
| 0.08       | Fang X, 2012, IEEE COMMUN SURV TUT, 14, 944 |
| 0.08       | Clement-nyms K, 2010, IEEE T POWER SYST, 25, 371 |
| 0.08       | Moslehi K, 2010, IEEE T SMART GRID, 1, 57 |
| 0.06       | Ipakchi A, 2009, IEEE POWER ENERGY M, 7, 52 |
| 0.06       | Galli S, 2011, P IEEE, 99, 998 |
| 0.06       | Palensky P, 2011, IEEE T IND INFORM, 7, 381 |
Table 5: Top document co-citation based on frequency in agent-based smart grid research (Authors analysis on collected data from WoS)

| Frequency | Author            | Year | Source                      |
|-----------|-------------------|------|-----------------------------|
| 164       | Mohsenian-rad AH  | 2010 | IEEE T SMART GRID           |
| 118       | Fang X            | 2012 | IEEE COMMUN SURV TUT        |
| 115       | Mohsenian-rad AH  | 2010 | IEEE T SMART GRID           |
| 96        | Palensky P        | 2011 | IEEE T IND INFORM           |
| 95        | Farhangi H        | 2010 | IEEE POWER ENERGY M         |
| 89        | Gungor VC         | 2011 | IEEE T IND INFORM           |
| 85        | Siano P           | 2014 | RENEW SUST ENERG REV        |
| 74        | Zimmerman RD      | 2011 | IEEE T POWER SYST           |
| 66        | Ipakchi A         | 2009 | IEEE POWER ENERGY M         |
| 65        | Mcarthur SDJ      | 2007 | IEEE T POWER SYST           |

2. Analysis of journals

Our next analysis is to identify the core journals of the domain. This can be noticed in Figure 4. The pink ring around the nodes in the network shows that there one node in the network with more than 0.1 centrality. “IEEE Transaction on Smart Grid” has the largest number of highly cited publications. The second largest number of publications is associated with the “IEEE Transaction on Power Systems”.

Table 6 shows the list of top ten journals based on citation counts. We can note here that the top venue for smart grid research is IEEE Transaction on Smart Grid and IEEE Transaction on Power Systems. These journals are mostly relevant to the research topic of “Agent-based smart grid”. Other journals like IEEE Transaction on Power Delivery, Renewable Sustainable Energy Review, IEEE Industrial Electronic, and Applied Energy are also representing relevance in the research of “Agent-based smart grid”.

Table 6: Top journals based on citation
(Authors analysis on collected data from WoS)

| Citation | Abbreviated Title          |
|----------|----------------------------|
| 1868     | IEEE T SMART GRID          |
| 1776     | IEEE T POWER SYST          |
| 774      | IEEE T POWER DELIVER       |
| 700      | RENEW SUST ENERG REV       |
Table 7 shows top journals based on centrality. “Nature” has the highest centrality value of 0.26 among all the other journals in the domain. “IEEE Transaction on Smart Grid”, and “IEEE Transaction on Power Systems” have same centrality value of 0.17 and listed at second and third position respectively. We also noticed that “Renewable and Sustainable Energy Review”, “Lecture Notes in Computer Science”, and “IEEE Transaction on Power Systems” are also some of the top journals of the “Agent-based smart grid” research.
Table 8 shows the list of top journals based on frequency. Here, the results are sorted according to the frequency of the publications and show different set of key journals. By frequency analysis of top journals, it can be noticed that “IEEE Transaction on Smart Grid” is at the top having 1868 frequency value. “IEEE Transaction Power Systems” and “IEEE Transaction Power Delivery” follow with 1776 and 774 frequency values respectively. This is followed by “Renewable Sustainable Energy Review”, “IEEE Transaction Industrial Electronic” and “Applied Energy” with frequencies 700, 677, 654 respectively. Next “Power IEEE” has published 649 articles. “Electric Power System Research”, “IEEE Transaction Industrial Informatics”, “Int. Journal of Electrical Power” and “Energy” journals are also top venues of “Agent-based smart grid” research.

**Table 7:** Top journals based on centrality

| Centrality | Journal Name                  |
|------------|-------------------------------|
| 0.26       | NATURE                        |
| 0.17       | IEEE T SMART GRID             |
| 0.17       | IEEE T POWER SYST             |
| 0.11       | RENEW SUST ENERG REV          |
| 0.10       | LECT NOTES COMPUT SC          |
| 0.10       | IEEE T POWER SYSTEMS          |
| 0.10       | P IEEE INT C SYST MA          |
| 0.09       | IEEE T POWER DELIVER          |
| 0.09       | IEEE J SEL AREA COMM          |
| 0.09       | P IEEE POW EN SOC GE          |

**Table 8:** Top journals based on frequency

Authors analysis on collected data from WoS

| Frequency | Source                        |
|-----------|-------------------------------|
| 1868      | IEEE T SMART GRID             |
| 1776      | IEEE T POWER SYST             |
| 774       | IEEE T POWER DELIVER          |
| 700       | RENEW SUST ENERG REV          |
| 677       | IEEE T IND ELECTRON           |
| 654       | APPL ENERG                    |
| 649       | P IEEE                        |
| 647       | ELECTR POW SYST RES           |
| 631       | IEEE T IND INFORM             |

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3. Analysis of categories

Our next focus is on the analysis of different categories in the “agent-based smart grid” research. Figure 6 shows the network of top categories. The detailed analysis of the subject categories is shown Table 9,
Table 10 and Table 11.

The top ranked category by centrality is “Engineering”, with centrality of 0.40. The second one is “Engineering, Electrical and Electronic, with centrality of 0.22. The third and fourth are “Computer Science and Information Systems” and “Science and Technology”, with centrality of 0.11. The fifth is “Physics” with centrality of 0.10. It is followed by “Computer Science”, “Energy and Fuels”, “Computer Science and Artificial Intelligence”. It is observed that the category “Computer Science and Interdisciplinary applications” has the lowest value of centrality among all other categories.

Next, we present an analysis of burst in subject categories.
Table 10 shows top categories based on burst. Here, it is noticed that “Computer Science, theory and methods” have the highest burst in 2009. Next, there are two categories related in different time span that are “Engineering, environmental”, and “Computer science, hardware and architecture”. It is followed by “Environmental Science and Ecology”, with bursts of 3.66. The last one is “Mathematics and Interdisciplinary applications”, with bursts of 3.57.

We also analyzed top categories based on frequency. It is shown in Table 11. Through frequency analysis of different categories, we come up with the almost same set of results. Here, again “Engineering” has topped the list with 2744 articles. It is followed by “Engineering, Electrical and Electronics” with 2397 published articles. It is noticed that “Energy and Fuels”, and “Computer Science” have close frequency value. Through frequency and centrality analysis, it is observed that the smart grid research is mostly related to the engineering, mathematics, and computer science.

![Top categories network](image)

**Figure 6:** Top categories network  
(Authors analysis on collected data from WoS)

**Table 9:** Top categories based on centrality  
(Authors analysis on collected data from WoS)
| Centrality | Category                                           |
|------------|----------------------------------------------------|
| 0.40       | Engineering                                        |
| 0.22       | Engineering, Electrical and Electronics            |
| 0.11       | Computer Science and Information systems           |
| 0.11       | Science and Technology                             |
| 0.11       | Physics                                            |
| 0.10       | Computer Science                                   |
| 0.08       | Energy and Fuels                                   |
| 0.08       | Engineering and Mechanical                         |
| 0.07       | Computer Science and Artificial Intelligence       |
| 0.06       | Computer Science and Interdisciplinary applications|
Table 10: Top category based on burst  
(Authors analysis on collected data from WoS)

| Bursts | Category                                        | Year   |
|--------|------------------------------------------------|--------|
| 14.04  | Computer Science, theory and methods           | 2009   |
| 5.86   | Engineering and environmental                  | 2013   |
| 5.57   | Computer Science, hardware and architecture    | 2009   |
| 3.66   | Environmental Science and ecology              | 2010   |
| 3.57   | Mathematics and Interdisciplinary applications | 2014   |

Table 11: Top category based on frequency  
(Authors analysis on collected data from WoS)

| Frequency | Category                                      |
|-----------|-----------------------------------------------|
| 2744      | Engineering                                   |
| 2397      | Engineering, Electrical and Electronics       |
| 1150      | Energy and Fuels                              |
| 1081      | Computer Science                              |
| 475       | Telecommunication                             |
| 359       | Automation and Control systems                |
| 338       | Computer Science, theory and methods          |
| 335       | Computer Science and Information system       |
| 241       | Computer Science, hardware and architecture   |
| 238       | Computer Science and Artificial Intelligence  |

4. Analysis of countries:

In this section, we present an analysis of the agent-based smart grid research across different countries. Figure 7 shows network of top countries based on centrality. Here, different countries are shown in a visualized form that is involved with agent-based smart grid research. Thus the network shows the top country is United States of America. This is followed by some other countries such as Germany, England, France, Canada, and China.

The top ranked item by citation counts is USA in 2000, with citation counts of 856. The second one is China (2010), with citation counts of 709. The third is Canada (2010), with citation counts of 243. The 4th is Germany (2000), with citation counts of 231. The 5th is Italy (2012), with citation counts of 211. Next, India, Iran, England, Australia, and France are also listed top in countries based on citation.
Table 12: Top countries based on citation
(Authors analysis on collected data from WoS)

| citation counts | references                             | cluster # |
|-----------------|----------------------------------------|-----------|
| 856             | USA, 2000, SO, 0, 0                     | 3         |
| 709             | PEOPLES R CHINA, 2010, SO, 0, 0         | 2         |
| 243             | CANADA, 2010, SO, 0, 0                  | 1         |
| 231             | GERMANY, 2000, SO, 0, 0                 | 0         |
| 211             | ITALY, 2012, SO, 0, 0                   | 0         |
| 185             | INDIA, 2012, SO, 0, 0                   | 2         |
| 165             | IRAN, 2013, SO, 0, 0                    | 1         |
| 155             | ENGLAND, 2011, SO, 0, 0                 | 1         |
| 149             | AUSTRALIA, 2010, SO, 0, 0               | 1         |
| 126             | FRANCE, 2010, SO, 0, 0                  | 0         |

Table 13 shows the list of top countries based on centrality. The top ranked item by centrality is USA, with centrality of 0.32. The second one is Germany with centrality of 0.15. The third is England, with centrality of 0.15. The 4th is France with centrality of 0.14. The 5th is Canada with centrality of 0.12. It is followed by China with centrality of 0.11. The 7th is Australia with centrality of 0.07.

Figure 7: Network of top countries
(Authors analysis on collected data from WoS)
Table 13: Top countries based on centrality
(Authors analysis on collected data from WoS)

| Centrality | Country   | Year |
|------------|-----------|------|
| 0.32       | USA, 2000 | 2000 |
| 0.15       | Germany   | 2000 |
| 0.15       | England   | 2011 |
| 0.14       | France    | 2010 |
| 0.12       | Canada    | 2010 |
| 0.11       | China     | 2010 |
| 0.07       | Australia | 2010 |
| 0.07       | Portugal  | 2010 |
| 0.07       | Turkey    | 2012 |
| 0.06       | Italy     | 2012 |

Table 14: Top countries based on frequency
(Authors analysis on collected data from WoS)

| Frequency | Author |
|-----------|--------|
| 856       | USA    |
| 709       | China  |
| 243       | Canada |
| 231       | Germany|
| 211       | Italy  |
| 185       | India  |
| 165       | Iran   |
| 155       | England|
| 149       | Australia|
| 126       | France |

5. Analysis of Institutes

In this section, we present visual analysis of top institutions on agent-based smart grid research. Figure 8 shows top institutions in a visual form. Here, we can see that Tsinghua University is the most central as well as highly cited node among all other institutions. North China Electric Power University, Delft University of Technology, Chinese Academy of Science, and COMSATS University Islamabad, Pakistan are also among top institutions in the agent-based smart grid research.
A visual analysis of the history of the burstness of top institutions is shown in Figure 9. This shows the list of those universities that are active in the agent-based smart grid research. Here, we see that Pacific NW NatLab has the strongest and longest citation burst among all other institutes from 2010 to 2016. It is followed by University of Auckland and University of Tennessee. It is found that National University of Singapor and Sherif Univeristy of Technology have shortest citation burst.
Next, we present an analysis of top institutions based on centrality. This has been shown in Table 15. The top ranked item by centrality is Tsinghua University with centrality of 0.13. The second one is Delft University of Technology, with centrality of 0.12. The third is Tech University Denmark, with centrality of 0.09. The 4th is University Alberta with centrality of 0.09. The 5th is Chinese Academy of Science, with centrality of 0.08. The 6th is Islamic Azad University with centrality of 0.07. The Aalborg University, Southeast University, Politecn Milan and Nanyang Technology University have centrality of 0.06 and lowest positions on the list.

Table 15: Top institutions based on centrality
(Authors analysis on collected data from WoS)
Our next focus is on the analysis of institutions based on frequency of publications. This has been shown in Table 16. It can be noted that North China Electrical Power University has the highest ranking with the frequency of 63 publications. Tsinghua University is followed by Technical University of Denmark with the frequency of 43 and 37 respectively. Next, COMSATS Institutes of Information Technology has 35 published articles. Next, the list shows University of Alberta and Aalto University. It is observed that Tianjin University has lowest publication frequency among others.

**Table 16: Top institutions based on frequency**
(Authors analysis on collected data from WoS)

| Frequency | Institutions                                           |
|-----------|--------------------------------------------------------|
| 63        | North China Elect Power Univ                           |
| 43        | Tsinghua Univ                                         |
| 37        | Tech Univ Denmark                                      |
| 35        | COMSATS Inst Informat Technol                         |
| 33        | Univ Alberta                                          |
| 32        | Aalto Univ                                             |
| 31        | Delft Univ Technol                                     |
| 29        | Chinese Acad Sci                                      |
| 29        | Aalborg Univ                                          |
| 27        | Tianjin Univ                                           |

6. Analysis of co-author

In this section, we present an analysis of author co-citation network. In Figure 10, the co-author network has been shown. The detailed analysis is given in Table 17 and Table 18.

The top ranked item by citation counts is Nadem Javaid (Javaid et al., 2015) with citation counts of 47. The second one is Zita Vale (Silva et al., 2012) with citation counts of 26. The third is Zahoor Ali Khan (Javaid, Ilyas, et al., 2015) with citation counts of 21. The 4th is Tiago Pinto (Barreira et al., 2013) with citation counts of 17. The 5th is Valerity Vyatkin (Chia-han Yang et al., 2013) with citation counts of 16. The 6th is Zhu Han (Saad et al., 2012) with citation counts of 15. The 7th is Sebastian Lehnhoff (Hinrichs et al., 2014) with citation counts of 13. Next, Gulnara Zhabelova (Zhabelova & Vyatkin, 2012) and Hugo Morais (Silva et al., 2012) have citation counts of 11.

The top ranked item by bursts is Jamil Y. Khan (Nafi & Khan, 2012) in 2012, with bursts of 5.31. The second one is Gulnara Zhabelova (Zhabelova & Vyatkin, 2012) with bursts of 4.38. The third Valerity Vyatkin (Chia-han Yang et al., 2013) with bursts of 4.29. The 5th is Husheng Li
(Meng et al., 2011) with bursts of 4.15. The 6th is Jason Brown (Brown & Khan, 2012) with bursts of 3.46.

**Table 17:** Top author by citation count  
(Authors analysis on collected data from WoS)

| Citation counts | Author               |
|------------------|----------------------|
| 47               | Nadeem Javaid        |
| 26               | Zita Vale            |
| 21               | Zahoor Ali Khan      |
| 17               | Tiago Pinto          |
| 16               | Valeraity VyatkinV   |
| 15               | Zhu Han              |
| 13               | Sebastian Lehnhoff   |
| 11               | Umar Qasim           |
| 11               | Gulnara Zhabelova    |
| 11               | Hugo Morais          |

**Table 18:** Top authors by burst  
(Authors analysis on collected data from WoS)

| bursts   | references            | Year |
|----------|-----------------------|------|
| 5.31     | Jamil Y Khan          | 2012 |
| 4.38     | Gulnara Zhabelova     | 2010 |
| 4.34     | Umar Qasim            | 2015 |
| 4.29     | Valerity V. Yatkin    | 2010 |
| 4.15     | Husheng Li            | 2011 |
| 3.46     | Jason Brown           | 2012 |

**Figure 10:** Network of top co-authors  
(Authors analysis on collected data from WoS)
7. Analysis of cited authors

This section presents analysis of the cited-authors network. Figure 11 shows network of cited-authors in the domain. This network consists of 394 cited authors along with 7203 links. It is important to note here that there is a problem in the dataset. The CiteSpace identified a cited-author named as “Anonymous”. In terms of frequency it is a most cited and central node in the network. However, on searching online we found no such author with this name. The detailed analysis is discussed as following.

![Network of top cited authors](image)

**Figure 11:** Network of top cited authors  
(Authors analysis on collected data from WoS)

The top ranked item by centrality is (C. Wang & Mahadevan, 2011) with centrality of 0.16. The second one is (Amin, 2011) with centrality of 0.15. The third is (Rahimi & Ipakchi, 2010) with centrality of 0.14. The 4th is (Shao, Zhang, Pipattanasomporn, & Rahman, 2010) with centrality of 0.13. The 5th is (Kersting & Green, 2011) with centrality of 0.12. The 6th is (Bouxsein et al., 2010) with centrality of 0.12. The 7th is (Rudd, McArthur, & Judd, 2010) with centrality of 0.11. The 8th is (Dimeas & Hatzigiorgiou, 2010) with centrality of 0.09. The 9th is (Lopes, Soares, & Almeida, 2011) with centrality of 0.09.
Table 19: Top cited-authors based on centrality  
(Authors analysis on collected data from WoS)

| Centrality | References | cluster # |
|------------|------------|-----------|
| 0.16       | Wang C, 2011, SO, 0, 0 | 5         |
| 0.15       | Amin SM, 2010, SO, 0, 0 | 1         |
| 0.14       | Ipakchi A, 2010, SO, 0, 0 | 2         |
| 0.13       | Pipattanasomporn M, 2010, SO, 0, 0 | 1 |
| 0.12       | Kersting WH, 2011, SO, 0, 0 | 3         |
| 0.12       | Boyd S, 2010, SO, 0, 0 | 2         |
| 0.11       | Mcarthur SDJ, 2010, SO, 0, 0 | 1         |
| 0.10       | [Anonymous], 2010, SO, 0, 0 | 0         |
| 0.09       | Hatziargyriou N, 2010, SO, 0, 0 | 1         |
| 0.09       | Lopes JAP, 2010, SO, 0, 0 | 2         |

Table 19 shows the list of top cited-authors based on centrality. As discussed above, there exists a problem in the dataset. The tool identified a cited-author with the name “Anonymous” with the most 1030 citations. However, by searching on internet, we found no such author. Next, Mohsenian-rad (Mohsenian-Rad & Leon-Garcia, 2011) is on second number with 273 citations. Gungor VC (Supriya, Magheshwari, Sree Udhyalakshmi, Subhashini, & Musthafa, 2015) is on third position with 169 citations. This is followed by Logenthiran T (Logenthiran, Srinivasan, Khambadkone, & Aung, 2010) with 151 citations. Next, Mcarthur SDJ (Rudd et al., 2010), Pipattanasomporn M (Shao et al., 2010), Feng X (Huang, Cui, Yin, Zhang, & Feng, 2017), Samadi P (Samadi, Schober, & Wong, 2011), and Palensky P (Palensky & Dietrich, 2011) are also listed as top cited-authors based on frequency.

Table 20: Top cited-authors based on frequency  
(Authors analysis on collected data from WoS)

| Freq | Author |
|------|--------|
| 1030 | [Anonymous] |
| 273  | Mohsenian-rad AH |
| 169  | Gungor VC |
| 151  | Logenthiran T |
| 149  | Mcarthur SDJ |
| 146  | Pipattanasomporn M |
| 143  | Fang X |
| 134  | Samadi P |
| 126  | Palensky P |
Summary of results

In this paper, we have adopted CiteSpace (a scientometric analysis tool) for different of analysis on the agent-based smart grid research. The key focus of this review was to give an overview of the emerging trends and dynamic of the domain over time. In the following section, we discuss our key findings.

Firstly, through cluster analysis, we found that cluster #0 was the largest cluster containing 80 nodes in the average year of 2011. The mutual index terms in this cluster were demand response, smart home and appliance scheduling. The articles by Mohsenian-rad AH, 2010 Fang X, 2012, are the key turning points in the domain.

Our next analysis was to identify key journals, authors, countries, institutions, and subject’s categories. Our analysis produced various interesting results. Next, we discuss these analyses.

In the analysis of key journals, we noted that the “IEEE Transaction on Smart Grid” has the largest number of highly cited papers in this domain. This journal also has most number of published articles in the domain. The journal “Nature” is the most central journal in the list.

In the top cited-author analysis, we noted that “Wang C., 2011” has the strongest burst among all authors in the list. We also performed analysis of most cited authors and found that “Wang C, 2011” is mostly cited authors in the research of agent-based smart grid. His area of research is smart grid, physical system, wireless sensor network, and security.

In the top countries analysis, we noted that “USA” is top country among all others based on frequency as well as citation. Others countries like China, Canada, Germany, and France are also actively work in the domain.

On the analysis of top institutions, we noted that “Pacific NW NatLab” has strongest and longest citation burst in the duration of 2010 to 2014. Based on frequency, “North China Elect. Power University” is on the top among all other institutes. Based on centrality score, “Tsinghua University” has top the list.

The analysis of top categories showed that the category “Engineering” leads over other categories with frequency 2744 and 0.40 centrality value. Category analysis showed that the work on agent-based computing of smart grid is multi-discipline. Engineer, computer scientist, physician, and environmental scientists all are working the domain.
Conclusions

In this paper, we have presented a detailed bibliographic review on agent-based smart grid research. The bibliographic data was collected from WoS database during the period of 1992 to 2019. The dataset was contained all journals, conferences, and workshop research work.

Our review showed various interesting results. The analysis showed that the domain gain significant research interest in 2007. Wang C, 2011 is most cited author in the domain. From journal perspective, the most cited journal is IEEE Transaction on Smart Grid. It contributed highest number of publications in the domain. The USA is most productive country in the domain while Pacific NW NatLab is most cited institute among all other institutions. In the category analysis, we found that this domain is multi-disciplinary domain. Researchers from engineering, computer science, and environmental science are working the smart grid research by using agent-based computing technology.

The possible extension of this work can be to explore the demand response, smart home, electric vehicles research topics of the domain.

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