Energy theft problem in power systems: A-state-of-the-art

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***Abstract*— The existing power systems as well as the smart grids utilize a number of advanced computing, networking and measurement technologies that improve their planning and operation targeting to a full automated system in terms of monitoring and control. As power systems become more complicated, they face a combination of known and unknown vulnerabilities and threats that are more targeted and sophisticated. Among them, malicious activity, influencing the measuring devices, is of major importance since it can instantaneously result in the physical operation and reliability of the grid. Conventional and smart energy meters incorporated to power systems are of the most vulnerable, to actions trying to manipulate them, measuring devices. The problem of conventional or smart energy meters manipulation targeting to influence the power system operation and reliability is known as the energy theft (ENT) problem. This problem has become of major importance in many countries all over the world. The energy theft is happening mainly in transmission and distribution level. In order to reduce the impact of energy theft, there are many methods that have been proposed in the literature. This paper presents a state-of-the-art survey for the energy theft problem solution.**

***Keywords*-- Energy theft, Power Systems, Smart Grid, Smart meters, State-of-the-art.**

I. INTRODUCTION

The electric power sector is undergoing many changes that have leading to the implementation of a new power system characterized as smart grid [1]. Smart grids utilize several advanced computing, networking and measurement technologies. One of those new technologies is the smart meters. Smart meters are electronic devices recording electric energy consumption and transfer the information needed through communication channels to the electricity supplier for monitoring and billing. Smart meters typically record energy hourly or more frequently, and report at least daily. Among the most significant problems that must be addressed in modern power grids is the energy theft problem (ENT). The ENT problem is increasing in most regions of the world having financial impacts on the incoming profit from the electricity sales and the charging of consumers. In order to reduce the effects of this phenomenon, many methods have been published in the literature. This paper makes a detailed bibliographic analysis of 30 selected works, which satisfy the criterion each work to have more than ten citations.

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 ENT problem literature, in terms of the most productive and highest-impact authors, institutions, and regions in worldwide ENT problem 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

Metadata for publications from IEEE Xplore and other digital libraries are used for this analysis. Information about the title, abstract, authors, author affiliations, references, and keywords are used to complete the bibliographic research. Journal articles and conference papers having more than ten citations and concerning the ENT problem are considered. For further quantification and estimation of the impact of these papers, the Google Advanced Scholar Search was used to download citation information during January 2019.

Initially, the total of the publish works downloaded were classified as either journal articles or conference papers. Secondly, data concerning authors' full names avoiding their underestimation in terms of multiple affiliations. Moreover, in case of institutions and countries/regions, the multiple affiliations were considered independently. The adjusted productivity score (APS) [2], [3], is used to estimate the productivity of authors, institutions, and countries/regions. Considering 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:

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

where N is the number of papers of an author, n_i is the number of authors of the ith paper, and c_i is the number of citations of the ith paper.

In order to further quantify the impact of individual authors, institutions, and countries/regions, the adjusted citation score (ACS) is introduced. The ACS index can be defined as the sum of citation credits of all his/her publications [3], [4]:

$$ACS = \sum_{i=1}^{N} \frac{c_i}{n_i} \tag{2}$$

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

III. Bibliographic Analysis Results

A. Selection Criterion

Works related with the ENT problem having more than ten citations have been considered in the following analysis.

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

According to the initial analysis performed for papers between 2008 and January 2019, a total of 30 papers with more than ten citations have been published in journals and conferences [5]−[34]. These 30 papers include 109 authors from 48 institutions in 21 countries/regions. Fig. 1 shows the total number of ENT papers per year having more than ten citations in January 2019.

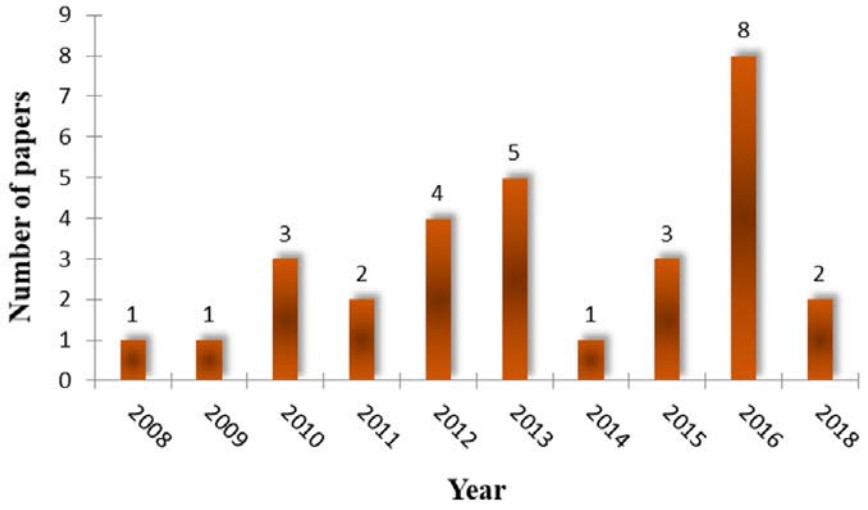

Fig. 1. Distribution of the number of papers per year dealing with the ENT problem solution having more than ten citations in January 2019.

C. Productivity Analysis

Table I provides the most productive among the 109 authors related with the ENT problem research, sorted by APS.

TABLE I
Most Productive Authors Sorted by APS

Rank	Name	Counts	APS
1	A. A. Cardenas	3	0.95
2	S. A. Salinas	2	0.83
2	P. Li	2	0.83
4	R. Berthier	2	0.53
4	S. McLaughlin	2	0.53
4	W. H. Sanders	2	0.53
7	G. A. Schwartz	2	0.45
7	S. Amin	2	0.45
8	T. Muso	2	0.39

TABLE II
MOST PRODUCTIVE INSTITUTIONS SORTED BY APS

Rank	Institution	APS
1	University of Illinois, Urbana-Champaign	2
1	Mississippi State University	2
2	Pennsylvania State University	1,4
3	University of California, Berkeley	1,1
4	University of Alabama, Tuscaloosa	1
4	KU Leuven	1
4	Toshiba Research Europe Ltd., Bristol	1
4	University of Mines and Technology, Tarkwa	1
4	UNESP/FEIS, São Paulo	1
4	Walchand College of Engineering, Sangli	1
4	Princeton University, NJ	1
4	University of British Columbia, Vancouver	1
4	University of Toledo	1
4	Bangladesh University of Engineering and Technology	1

Table II presents the ten most productive institutions in a list of 48 institutions that have been involved in the energy theft problem research based on APS. The three most productive institutions are from USA, whereas the flagships in productivity are the university of Illinois and the Mississippi State University. Table III presents the ten most productive countries/regions with ENT publications based on the location of the institutions and considering the APS index. The three most productive countries in descending order is the USA, followed by China and India.

TABLE III
MOST PRODUCTIVE COUNTRIES SORTED BY APS

Rank	Institution	APS
1	USA	12,4
2	PRC	2,07
3	INDIA	2
4	CANADA	1,67
5	ROC	1
5	BELGIUM	1
5	LUXEMBOURG	1
5	UK	1
5	NETHERLAND	1
5	GHANA	1
5	BRAZIL	1
5	SPAIN	1
5	BANGLADESH	1

D. Impact Analysis

The 30 papers related with the ENT problem and have more than ten citations been cited 2347 times, which means that on average each of these papers is cited 78.23 times. Table IV presents the ten most frequently cited papers. The most frequently cited authors in a list of 108 cited authors and the most often cited institutions in a list of 80 cited institutions are reported in Tables V and VI, respectively. The most cited authors are C. Efthymiou and G. Kalogridis, whereas the most cited institutions are Toshiba Research Europe Ltd., Pennsylvania State University, and University of Illinois.

TABLE V
MOST CITED AUTHORS (TOP TEN)

Rank	Name	Cites	ACS
1	C. Efthymiou	580	290.00
1	G. Kalogridis	580	290.00
3	S. McLaughlin	262	87.33
3	D. Podkuiko	262	87.33
3	P. McDaniel	262	87.33
6	R. Berthier	231	77.00
6	W. H. Sanders	231	77.00
6	H. Khurana	231	77.00
9	P. Jokar,	124	41.33
9	N. Arianpoo,	124	41.33
9	V. C. M. Leung	124	41.33

TABLE IV
MOST CITED PAPERS

Rank	Title	Authors	Year	Ctry / Reg	Cites
1	Smart Grid Privacy via Anonymization of Smart Metering Data	C. Efthymiou, G. Kalogridis	2010	UK	580
2	ENT in the Advanced Metering Infrastructure	S. McLaughlin, D. Podkuiko, P. McDaniel	2009	USA	262
3	Intrusion Detection for Advanced Metering Infrastructures: Requirements and Architectural Directions	R. Berthier, W. H. Sanders, H. Khurana	2010	USA	231
4	Energy-theft detection issues for advanced metering infrastructure in smart grid	R. Jiang, R. Lu, Y. Wang, J. Luo, C. Shen, X. Shen	2014	PRC, SINGAPORE, CANADA	145
5	Electricity Theft Detection in AMI Using Customers' Consumption Patterns	P. Jokar, N. Arianpoo, V. C. M. Leung	2016	CANADA	124
6	Non-Technical Loss analysis for detection of electricity theft using support vector machines	J. Nagi, A. M. Mohammad, K. S. Yap, S. K. Tiong, S. K. Ahmed	2008	MALAYSIA, BAHRAIN, SWITZERLAND	107
7	A Multi-Sensor ENT Detection Framework for Advanced Metering Infrastructures	S. McLaughlin, B. Holbert, A. Fawaz, R. Berthier, S. Zonouz	2013	USA	83
8	Evaluating Electricity Theft Detectors in Smart Grid Networks	D. Mashima, A. A. Cárdenas	2012	USA	79
8	Support vector machine based data classification for detection of electricity theft	S. S. S. R. Depuru, L. Wang, V. Devabhaktuni	2011	SPAIN	79
10	Decision Tree and SVM-Based Data Analytics for Theft Detection in Smart Grid	A. Jindal, A. Dua, K. Kaur, M. Singh, N. Kumar, S. Mishra	2016	INDIA	67

TABLE VI
MOST CITED INSTITUTIONS (TOP TEN)

Rank	Title	Ctry/Reg	Cites	ACS
1	Toshiba Research Europe Ltd., Bristol	UK	580	580.00
2	Pennsylvania State University	USA	262	262.00
3	University of Illinois	USA	231	231.00
4	University of British Columbia	CANADA	124	124.00
5	Mississippi State University	USA	85	85.00
6	University of Toledo	SPAIN	79	79.00
7	Eindhoven University of Technology	NETHERLANDS	53	53.00
8	Bangladesh University	BANGLADESH	41	41.00
9	Georgia Institute of Technology	USA	79	39.50
9	Fujitsu Laboratories of America	USA	79	39.50

IV. CONCLUSIONS

This paper proposes a survey on the ENT problem research based on the publications in journals and conferences. The main results show that mainly USA researchers and institutions are the dominant on the ENT bibliography. The most cited authors are C. Efthymiou and G. Kalogridis, whereas the most productive are A. A. Cardenas, S. A. Salinas, and P. Li. The most productive institutions are the University of Illinois, the Mississippi State University and the Pennsylvania State University, whereas the most productive countries are USA, China, and India, respectively.

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