Power Theft Detection in Microgrids

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Abstract: Theft of electricity amounts to 1.5% GDP, of most of the developing nations like India. Hence there is a great need to detect power thefts in developing nations. In this paper, we have proposed a wireless network based infrastructure for power theft detection which caters to other functional requirements of the microgrid such as renewable energy integration, automatic meter reading etc. Algorithm for power theft detection (PTDA) which is proposed in this paper, works in the distributed intelligent devices of the microgrid infrastructure for power theft detection. The coordinated action of intelligent devices with PTDA in the microgrid infrastructure enables not only the detection of power theft, but the localization of power theft in the micro-grid. PTDA increases the 1) cost of communication 2) energy consumption of intelligent devices 3) packet latency, if any critical data is piggy backed with power theft data in micro-grid. To solve these issues, we have proposed EPTDNA (Efficient Power Theft Data Networking Algorithm) which uses the frequency of power theft detection and average power draw for power theft, for the efficient routing of power theft. The performance analysis and results given in this paper shows how EPTDNA solves the major issues with PTDA.

1 INTRODUCTION

Smart Grid is the new generation electric grid technology whose pivotal network is a wireless network (Amin and Wollenberg, 2005). Microgrids are small smart power grids, which is a part of smart distribution grid, that can operate in islanded mode or in grid-connected mode. The existing grid system in developing nations is suffering due to a lot of problems which affects the country's economic growth, one of which is power theft (Farhangi, 2010). The microgrid technology solves all these problems to some extent. The features of microgrid include, distributed generation of electricity, integration of renewable energy source, power theft detection, line fault detection, self-healing, advanced metering infrastructure, and automated billing and controlling (Hartono, Budiyanto and Setiabudy, 2013). The research paper (Myoung, Kim and Lee, 2010) introduces KEPCO's field area network (FAN) architecture and research for smart distribution automation system (DAS) and advanced metering infrastructure (AMI). However, the current research work in the smart grid or microgrid area does not fully support real-time, reliable communications and necessary smart grid services.

Power theft is considered as a bane of the power grid in most of the developing nations. Nearly, 30% of the generated electricity has not been billed in these nations because of the power theft losses and transmission losses. Hence there is an urgent need from the utility side to detect and locate the power theft. In this paper, we have proposed a wireless based microgrid infrastructure for power theft detection. The power theft detection algorithms (PTDA) inside the intelligent devices in the microgrid infrastructure detect and localize the power theft in the grid. In PTDA, the messages regarding the current draw or injection at each intelligent device are transmitted to next nearby node very often. This introduces three issues namely, 1) cost of communication increases with increase in number of message transfer, if the communication module is not using ISM band, 2) even if, SMs and SDNs are low powered devices, full time switch on of these devices may contribute to the un-sustainability of the microgrid in terms of energy, since they are powered by micro-grid, 3) if the energy consumption data from the consumers are piggy backed with the multi-hop current flow data for power theft detection, then it may introduce large latency and will affect the billing process. To solve

these issues we have proposed an algorithm called Efficient Power Theft Data Networking Algorithm (EPTDNA) which works with PTDA.

The major contributions of this research paper are:

1. Microgrid infrastructure for power theft detection which caters to other functional requirements of micro-grid.

2. Power theft detection algorithm (PTDA) which uses Kirchhoff's Current Law (KCL), for the detection and localization of power theft.

3. Efficient Power Theft Data Networking Algorithm (EPTDNA) for efficient routing of power theft data, which solves three issues of PTDA.

The rest of the paper is organized as follows: Section 2 discusses the related works and Section 3 gives a wireless networks based microgrid infrastructure for power theft detection. Section 4 describes the power theft detection algorithm (PTDA). Section 5 describes the problems of PTDA and Efficient Power Theft Data Networking Algorithm (EPTDNA) which solves the issues of PTDA. Section 6 describes the performance evaluation and results which shows how EPTDNA solves the issues with PTDA which follows conclusion in section 7.

2 RELATED WORKS

In most of the developing nations power theft is happened by drawing power from the overhead grid lines which are bare conductors. Usually, the unauthorized consumers who are committing the theft may not have a smart meter associated to them. Most of the research papers addressed the power theft committed by several cyber attacks.

The reference publication (Mashima and Cardenas, 2012), the authors proposes the first threat model for the use of data analytics, to detect the anomalies of the data received from advanced metering infrastructure. The reference paper (Nikovski, Wang, Esenther, Sun, Sugiura, Muso and Tsuru, 2013) proposes a method for power theft detection based on the data collected by the smart meters in the smart grid. They used predictive models for calculating the technical losses in electrical distribution networks and used these models for power theft detection. The dissertation (Depru, 2012) presents an encoding and classification scheme that simplifies the energy consumption pattern and maps them to the corresponding irregularities in the consumption. The reference paper (Devidas and Ramesh, 2010)

describes the method for detection and localization of power theft in smart grids. But it has not considered the bidirectional electricity flow in microgrids. In this paper, we have proposed algorithms for power theft detection in micro-grids and for efficient routing of power theft data.

The research papers (Salinas, Li and Li, 2012), (Weckx, Gonzalez, Tant, Rybel, Driesen, 2012) and (McLaughlin, Holbert, Zonouz and Berthier, 2012) deals with the power theft created due to several cyber attacks. Solving of power theft by placing intelligent devices throughout the power grid and by computerised billing systems is explained in the reference paper (Amarnath, Kalaivani and Priyanka, 2013). It deals with the power theft due to smart meter tampering whereas our work deals with the power theft due to distribution line tampering, the kind of power theft that experiencing in developing nations.

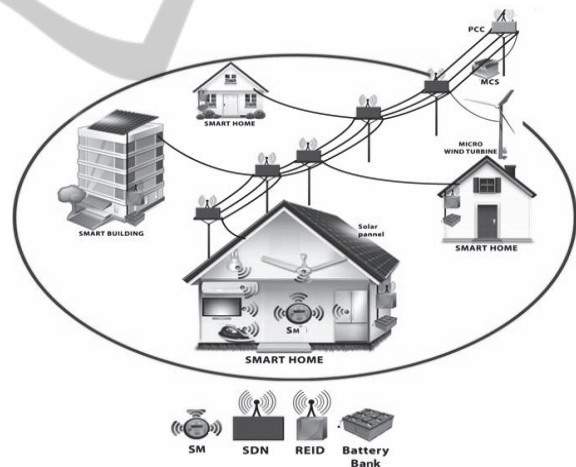## 3 MICROGRID INFRASTRUCTURE FOR POWER THEFT DETECTION

Figure 1: Microgrid infrastructure for power theft detection.

Microgrid infrastructure for power theft detection involves power grid and an overlay communication network. The detection of power theft is possible by integrating intelligent communication agents at different locations of the power grid. For power theft detection intelligent communication infrastructure are placed near all consumers and also on top of each and every pole. Such a microgrid is shown in the figure 1. Point of Common Coupling (PCC) is the point in the power grid at which the microgrid is

connected to the main grid.

The intelligent devices near the consumers are called Smart Meters (SMs), the intelligent devices on top of all the poles are called Smart Distribution Nodes (SDNs) and the intelligent devices associated to the renewable energy sources are called Renewable Energy Intelligent Device (REID). Microgrid Control Station (MCS) is the main control station of the micro-grid. SMs and SDNs measure the current flow towards or away from each consumer and distribution pole. SMs and SDNs have the capability to send data to other SMs or SDNs or MCS. These intelligent communication agents consists of the current sensors for measuring bidirectional current flow, microcontroller for processing data and communication module for sending the data to other intelligent agents. The MCS controls all the intelligent agents and takes care of the energy management inside the micro-grid.

The communication technology used for the transmission of data mainly depends on the transmission range, data rate and transmission cost. In India the maximum distance allowed between two transmission line posts in a secondary distribution grid is in the range of 40 to 50meters and the power theft data is not a huge sized data. Hence the recommended communication technologies for the intelligent agents for power theft detection are Zigbee or Wifi (Agarwal, Agarwal, Vyas and Sharma, 2013) (Datar, 2008). Even though, these are the recommended technologies for power theft detection functionally of microgrid, depending on other functionality of micro-grid, there can be a change in the communication technologies used by intelligent agents in the micro-grid.

4 POWER THEFT DETECTION ALGORITHM (PTDA)

The SMs and SDNs in the microgrid infrastructure are responsible for the detection of power theft in a microgrid. Assume *'SDN$_K$'* is the kth SDN in the microgrid *'M'*. Let *'n'* be the number of direct descendants (SMs and SDNs) of *'SDN$_K$'* as shown in figure 2(a). *'SDN$_K$'* measures the current flow through it using Kirchhoff's Current Law (KCL). Let *'i$_k$'* be the measured current by *'SDN$_K$'*.

'SDN$_K$' will also receives the current values with the direction information from all its descendants. It will sum all the current values got from its descendants. Let *'i$_{dk}$'* be the summation of descendants current values.
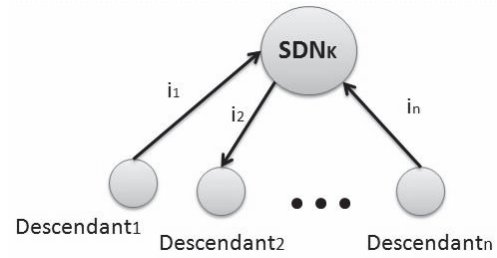

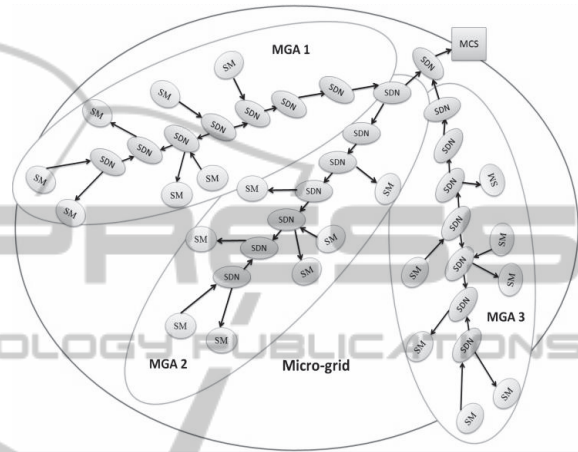Figure 2(a): 'n' descendants connected to the SDN 'K'.

Figure 2(b): Tree-like topology of microgrid and MGAs inside the micro-grid.

$$i_{dk} = \sum_{j=1}^{n} i_{dir}^j \times i_j \qquad (1)$$

If $i_k \neq i_{dk}$, then *'SDN$_K$'* decide a power theft has occurred and send the power theft information to the MCS. The Power Theft flag (*PT$_{flag}$*) will set *True* or *False* based on the detection of power theft in the line segment between *'SDN$_K$'* and its descendants. CP and PT represents data packets with current value and the power theft values respectively. The algorithm for detecting the power theft in *'SDN$_K$'* is as follows:

1. Measure i_k using KCL.
2. Send CP*msg*{*src$_{ID}$*, i_{dir}^k ,*i$_k$*, *time_stamp,dst$_{ID}$*} to next intelligent device.
3. *Wait(t<T$_{sec}$)* **until**
4. *Receive*[*CP$_1$,CP$_2$,...,CP$_n$*]
5. **if**(!*Receive*[*CP$_1$,CP$_2$,...,CP$_n$*]&&*t>T$_{sec}$*)
6. Discard the *CP$_1$,CP$_2$,...,CP$_n$*
7. After 'm' number of rejection of CPs,
8. Send message to MCS
9. Initiate communication network reorganization
10. **Go to** step2.
11. **end if**

12. **else if**$((Receive[CP_1,CP_2,...,CP_n]\&\&t<T_{sec})$
13.   Extract current values $i_1, i_2....i_n$.
14.   Insert sign according to the direction information, i_{dir}^j.
15. $i_{dk} = \sum_{j=1}^{n} i_{dir}^j \times i_j$
16. $Compare(i_k, i_{dk})$.
17. **if**$(i_k == i_{dk} - Tx_{loss} \pm Err_{val})$
18. $PT_{flag} = $ false
19. **end if**
20. **elseif**$(i_k != i_{dk} - Tx_{loss} \pm Err_{val})$
21. $PT_{flag} = $ true
22.   Send PT$msg\{src_{ID}, i_{dir}, i_{PT}, PT_{flag} = $ true, $time\_stamp, mcs_{ID}\}$ to MCS.
23. **end if**
24. **end if**

The SDN measures the current flow through it and wait T_{sec} until it receives the current values of its 'n' descendants. If the current values from all 'n' are not received till the time T_{sec}, then the SDN discards all the values and measures again the current value. After certain number of such rejection of data, SDN realizes a failure in the communication link or in the descendant node. Then SDN will either initiate reorganization of communication network or send a message to MCS regarding the issue. When the electric current travels through the distribution line, it experiences some loss due to heat which is termed as copper loss. The Tx_{loss} represents this copper loss. The current value that receives can be erroneous due to electromagnetic interference. The maximum allowed error is $\pm Err_{val}$. CP is the current data packet which contains the source ID, direction vector, current value, time stamp and destination ID. PT is the power theft data packet which contains source ID, direction vector of power theft current (i_{dir}), power theft current value (i_{PT}), power theft flag, time stamp and the ID of MCS. The packet structures of CP and PT messages are shown in figure 3(a) and figure 3(b).

Source ID	Direction vector	Current value(i)	Time stamp	Destination ID

Figure 3(a): Structure of current packet.

Source ID	Direction vector of PT current	PT current value	PT flag	Time stamp	MCS ID

Figure 3(b): Structure of power theft packet.

5 EFFICIENT NETWORKING OF POWER THEFT DATA

In the power theft detection method (PTDA) described in section 4, the messages regarding the current draw or injection at each node are transmitted to next nearby node very often. This introduces three issues namely, 1) cost of communication increases with increase in number of message transfer, if the communication module is not using ISM band (Baker, King and Welch, 2004), 2) even if, SMs and SDNs are low powered devices, full time switch on of these devices may contribute to the un-sustainability of the microgrid in terms of energy, since they are powered by microgrid, 3) if the energy consumption data from the consumers are piggy backed with the multi-hop current flow data for power theft detection, then it may introduce large latency and will affect the billing process. To solve these issues two questions need to be answered,

a) How often we need to check for power theft inside a microgrid?

b) How to determine whether the data has to hop through each and every intelligent device?

We propose an algorithm called Efficient Power Theft Data Networking Algorithm (EPTDNA) which works with PTDA to solve the above mentioned issues.

For the efficient networking, assume the microgrid has a tree-like topology as shown in figure 2(b), in which SMs and SDN are considered as nodes in the topology. The independent sub-branches of the microgrid tree are identified as different Microgrid Areas (MGAs) such as Frequently Identified MGA (FMGA), Occasionally Identified MGA (OMGA) and Extremely Unlikely Identified MGA (EUMGA) based on the full load in the sub-branches, total generation capacity in the sub-branches and the geographical terrain as shown in figure 2(b). The Microgrid Controlling Station (MCS) will find out the critical microgrid areas from the identified MGAs based on the frequency of the power theft detection data and the average theft current. Once the critical grid area is identified, then MCS decides the hop count (H) for the multi-hop transmission and the periodicity of the power theft check, based on the measure of criticality.

Let there are 'm' number of MGAs in a microgrid. The EPTDNA for efficient networking of power theft data in MCS of the microgrid is as follows:

1. **Phase I:**
2. Collect the power theft data from MGA_1, $MGA_2....MGA_m$ using the power theft detection

algorithm for T_c (in the order of days or weeks) time duration.

3. **Phase II:**
4. Calculate $\{F, \text{Avg}(i_{PT})\}$ for each MGA.
5. Classify MGAs based on $\{F, \text{Avg}(i_{PT})\}$ using algorithms such as medoid or k- means.
6. Get three classes namely *FMGA*, *OMGA* and *EUMGA*.
7. **for**(class 1 to class 3)
8. Calculate $\{\text{Avg}(F_{cl}), \text{Avg}(i_{cl})\}$
9. T_{cl}(unit is same as T_c) $= 1/\text{Avg}(F_{cl})$
10. Calculate $r = \text{Avg}(\text{Max}(i_{con}))/\text{Avg}(i_{PT})$
11. **if**($r \geq 1$)
12. $\tau_{cl} = T_{cl}$
13. Set $h_{cout} = [(N_{tot}/k)\text{-}1]$
14. **else**
15. $\tau_{cl} = T_{cl} \times r$
16. Set $h_{cout} = [N_{tot}\text{-}1]$
17. **end if**
18. Send $\text{T}_{PT}msg\{MCS_{ID}, \tau_{cl}, h_{cout}, MGA_{ID}, time\_stamp\}$ to MGAs in three classes.
19. **end**

In EPTDNA, MCS will collect the power theft data from all the MGAs under the control of the MCS using the power theft detection algorithm for T_c duration. The MCS calculates the frequency of data on power theft detection(F) of power theft detection and average power theft current value for each MGA. On this two-dimensional data, MCS run any classification algorithm and classify the MGAs into three classes. The three classes are Frequently Identified MGA (FMGA), Occasionally Identified MGA (OMGA) and Extremely Unlikely Identified MGA (EUMGA). Then for each derived class, the MCS again computes the average frequency of data on power theft detection(F_{cl}) and the average power theft current (i_{cl}). MCS finds T_{cl} using average of F_{cl}. For finding the ratio *'r'*, the MCS calculates the average current draw of the maximum power drawing consumers for MGAs. After computing the ratio *'r'*, it sets the time duration for power theft check (τ_{cl}) and the hop count (h_{cout}) for the power theft data for the MGAs in each class. N_{tot} is the total number of SDNs in the MGA and the factor *'k'* depends on the maximum communication range of the SDNs.

After finding out the τ_{cl} and h_{cout} for each class, the MCS will send this information to the MGAs in each class. Then the MGAs set the new values for τ_{cl} and h_{cout} and those values persist the next T_c duration. If τ_{cl} is too large, then random power theft check will be introduced for the MGAs. The next EPTDNA *Phase II* initiation happens in two cases: 1) After T_c duration 2) After the power theft

detection in random power theft check. Table 1 shows the description of notations used in this research work.

Table 1: Description of notations used in this research paper.

Notations	Description
i_k	The current flow measured by K^{th} SDN.
i_{kdir}	Direction vector of the current flowing through K^{th} SDN.
i_{dir}	Direction vector of the power theft current.
i_{dk}	Sum of the current flowing through all the descendants of Kth SDN.
Tx_{loss}	Transmission loss due to heat.
Err_{val}	Tolerance limit for the error in the received current value at SDN.
i_{PT}	Power theft current.
T_c	Time duration for power theft data collection for EPTDNA-Phase I.
F	Frequency of data on power theft detection for T_c duration.
F_{cl}	Frequency of data on power theft detection for T_c duration in a class.
i_{cl}	Power theft current in a class.
i_{con}	Current draw by the consumer.
τ_{cl}	Time duration after which periodic power theft check happens.
h_{cout}	Hop count of data transmission for power theft check.
N_{tot}	Total number of SDNs in a MGA.
k	Factor that determines the h_{cout} and depends on the maximum communication range of SDNs

6 PERFORMANCE ANALYSIS AND RESULTS

To show how EPTDNA with PTDA gives better

performance than PTDA alone, we assume the microgrid has fourteen MGAs with *'F'* and average of *'i$_{PT}$'* for 30 days as shown in table 2. We have applied k-means classification algorithm on the 2-D data in table 2 (Wilkin and Huang, 2007). The results of the classification algorithm are shown in figure 4 and table 3. Five MGAs are identified as FMGA, six MGAs are identified as EUMGA and three MGAs are identified as OMGA using k-means algorithm.

Table 2: Microgrid Areas in a microgrid with *'F'* and *'Avg(i$_{PT}$)'* used for the analysis.

MGA	F	Avg(i$_{PT}$) in Amperes
1	15	19
2	20	18
3	17	16
4	18	17
5	2	8
6	1	6
7	4	10
8	3	7
9	13	5
10	16	10
11	12	8
12	5	15
13	8	17
14	6	14

The 'Avg(F_{cl})' and 'Avg(i_{cl})' values are shown in table 4. From those values, 'T_{cl}', 'r' and 'τ_{cl}' values are calculated for the three classes as shown in table 5. The τ_{cl} values are derived based on the 'Avg(F_{cl})' and 'r' values. The Avg(Max(i_{con})) value for the microgrid is assumed as 15A.

In this case, the hop count (h_{cout}) for transmitting the data for PT check for MGAs inside the classes EUMGA depends on the factor 'k', which again depends on the communication range of SDNs used in the microgrid infrastructure. The 'h_{cout}' for FMGA and OMGA, depend on the total number of SDNs in those MGAs.

If in PTDA, the power theft check is done in every 15minutes for the whole micro-grid, then after every 15minutes the SDAs and SMs have to transmit the data through each and every node. Also the sleep duration for the nodes should be less than 15minutes. By using PTDA with EPTDNA, from the table 5, it is clear that the sleep duration of the nodes increases and the message complexity reduces
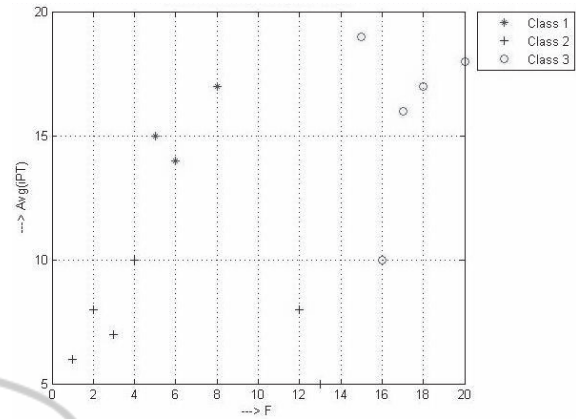

Figure 4: K-means plot using *'F'* and *'Avg(i$_{PT}$)'* from table 2.

Table 3: Microgrid areas (MGAs) in the identified classes.

MGA	F	Avg(i$_{PT}$) in Amperes
Class 3 - FMGA		
MGA -1	15	19
MGA -2	20	18
MGA -3	17	16
MGA -4	18	17
MGA -10	16	10
Class 2 - EUMGA		
MGA -5	2	8
MGA -6	1	6
MGA -7	4	10
MGA -8	3	7
MGA -9	13	5
MGA -11	12	8
Class 1 - OMGA		
MGA -12	5	15
MGA -13	8	17
MGA -14	6	14

Table 4: Avg(F_{cl}) and Avg(i_{cl}) values for the three classes.

Classes	Avg(F_{cl})	Avg(i_{cl}) in Amperes
Class 3 - FMGA	17.2	16
Class 2 - EUMGA	5.83	7.3
Class 1 - OMGA	6.3	15.33

relative to the PTDA without EPTDNA. As the cost for communication is directly proportional to the message complexity, by using EPTDNA along with PTDA, the cost for communication can be reduced. Increased sleep duration of the nodes implies the reduced energy consumption. Thus the effect of

Table 5: T_{cl}, r and τ_{cl} values for the three classes.

Classes	T_{cl} (in days)	r	τ_{cl}(in days)
Class 3 - FMGA	1.74	0.94	1.63
Class 2 - EUMGA	5.14	2.05	5.14
Class 1 - OMGA	4.74	0.98	4.63

energy consumption by SDNs or SMs in the un-sustainability of microgrid can be reduced. In PTDA with EPTDNA, the example case shows that the hop count is reduced in MGAs under EUMGA category. Thus the data latency is reduced in parts of the micro-grid, if the consumption data is piggy backed with the power theft detection data. Thus the three issues of PTDA without EPTDNA mentioned in section 4 are solved using EPTDNA.

7 CONCLUSIONS

In this paper we have proposed wireless network based solution for power theft, which is considered as a bane of power grid in most of the developing nations. We have proposed power theft detection algorithm (PTDA) which uses Kirchhoff's Current Law (KCL). We have identified three issues of PTDA when it will be used for micro-grids. To solve those issues with PTDA, we have proposed another algorithm called EPTDNA (Efficient Power Theft Data Networking Algorithm). The performance analysis and results given in section 6 shows how EPTDNA solves the issues with PTDA. In future, we are planning for a real-world deployment of microgrid infrastructure that enables efficient power theft detection and localization using EPTDNA together with PTDA.

ACKNOWLEDGEMENTS

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