Web Application for Power Grid Fault Management

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***Abstract*—Smart power grids have been introduced in many developed countries and facilitate more efficient and economical utilization of generated power. The components of such a grid are usually remotely monitored and selected components are controlled either manually or through advanced software programs. However, many countries still rely on an Automated Meter Reading (AMR) network. AMR meters periodically report electrical energy consumption information to a centralized location and can also (since they contain batteries) transmit indications of power outage as well as power restoration. We make use of these meters to create a web application that examines and detects faults (blackouts, brownouts and surges) in an electrical grid. This application complements any existing sensor networks and software so that no new equipment needs to be implemented.**

***Index Terms*—Application Software; AMR; Fault Detection; Internet of Things; Smart Grids**

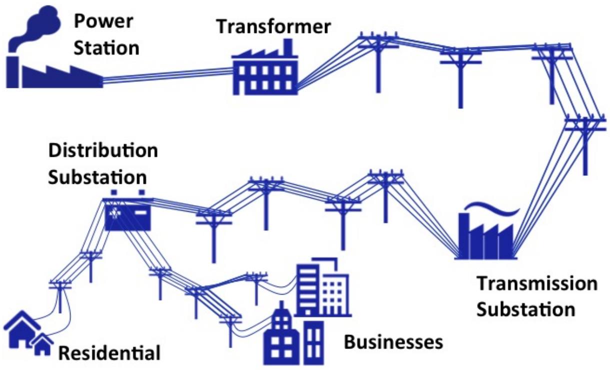


Fig. 1. Power Grid Architecture

I. Introduction

An electrical power grid is a network of electrical components used to supply, transmit and use electric power [1]. It comprises of many parts: power generating stations which produce the electrical power, transformers to convert the generator's voltage up to extremely high voltages for long-distance transmission and the distribution stations which step the transmission voltages down to distribution voltages for use by consumers (see Figure 1) [2]. This hierarchical structure has remained unchanged for many years. However, with demand rising sharply and new technology emerging, there has been a shift to develop smart grids. A smart grid generally refers to a class of technology people are using to bring electricity delivery systems into the 21st century by using computer-based remote control and automation. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries [3].

Smart grids use an Advanced Metering Infrastructure (AMI) to more efficiently support the transportation, distribution and consumption of electrical energy. It is an integrated system of smart meters, communications networks and data management systems that facilitate real-time two way communication between utilities and consumers [4]. Thus, AMI allows utilities to access an abundance of information. This information includes electrical consumption data, load profile data, demand, time-of-use, voltage profile data and power quality data [5]. AMI allows for more precise meter readings, earlier detection of meter failures, flexible billing cycles and reduced maintenance costs [6].

An AMI can also assist with outage management, allowing utilities to detect any faults (outages) and then determine the severity and location of the outage so that they can restore power quickly. Thus, fault detection and fault localization are very important. In contrast to AMI networks, Automatic Meter Reading (AMR) networks provide one way communication from the reader to the utility and is essentially used for reporting energy usage. These are less costly but have limited capability. In many developing countries AMR rather than AMI networks are available.

Current research has seen many novel developments in AMI networks rather than AMR networks especially for fault detection. Fault detection is one of the major problems that electrical companies face as they can cause loss of electrical power to customers, property damage and, depending on the fault, can injure humans. The type of fault strongly depends on the magnitude of the current, the location of the fault and the duration of the fault [7].

We propose an application that seeks to detect, isolate and help restore faults in the grid so as to reduce fault duration, number of customers affected [1]. Maps are used to provide visual inspection of each component in the electrical grid. It contains options to select certain components of the grid so that an in-depth analysis can be done. Furthermore, there are numerous graphs for real time analysis of the grid and its

[1]https://github.com/smhosein/tntec_web_app

components. Some graphs contain thresholds and when they are exceeded alerts are issued. It is an open-source application and thus not proprietary so that any company can utilize and enhance the application. Most importantly, this application does not require additional equipment or sensors to be installed in the network but it instead serves as a complement to any existing software.

II. Related Work

Previous work in this area typically assumes an AMI network and focuses on use of readings within the network using Intelligent Electronic Devices (IED) to detect faults. Here is a summary of some of this work. The paper by Singh et. al. [8] presents a technique to detect and classify the different shunt faults on transmission lines for quick and reliable operation of protection schemes hence their focus was on transmission line faults. Similarly the paper by Silva et. al. [9] also focuses on transmission line faults. The papers [10] and [11] do investigate fault localization but this is achieved through information within the network. In [12] they investigate the optimal placement of sensors within the network for outage detection. In the paper by Kezunovic et. al.[13] the authors address the issue of improving the accuracy of fault location methods in smart grids using an abundance of Intelligent Electronic Device (IED) data. Here again the work is network-centric as access to information from devices within the network is assumed. In the work by Zhang et. al. [14] a wireless sensor network is deployed and used for fault detection in the power grid.

There are few papers that utilize the AMR network. Chaure and Dhengre [15] did work to make a fault detection system using Zigbee and Embedded Base meter readings. This system tries to enable real-time metering, real-time monitoring and can also detect equipment damage and illegal use. There are many drawbacks with this system, the major ones being that extensive remodeling of current meters would need to be done and this would cost the company significant money to implement. In the work by Korhonen [16], the author developed a mathematical method for calibration of energy meters using AMR data. An algorithm was derived for recursive computation of meters systematic errors and their confidence intervals. This method works only when the grid configuration is set up properly, which would mean that for any electrical network that is not set up according to the paper the results would not be accurate. In the paper by [17], the authors used AMR readings to detect faults in district heating substations. However, this paper is very specific as it only looks at one part of the power grid structure and thus would not be applicable for large scale use.

There are some software programs that exist that seek to perform fault detection for power girds. ETAP [18] seeks to perform fault isolation and service restoration for the distribution network. It finds the section of the network that will be isolated due to a forced outage and provide information to the operator or planner regarding the customers affected. This product only looks at the distribution part of the power grid and it is proprietary and hence may require maintenance and upgrade costs. Another product is from GridSense [19], where they provide an overhead line monitoring system which performs all the traditional fault current indicator functions. In addition to being proprietary, some hardware needs to be installed and it is also specific to lines in the power grid. Trilliant [20] seeks to perform fault detection but in AMI smart grids. It also requires a two-way network configured to communicate with site components. There is Tollgrade's product Lighthouse [21] which performs fault detection, isolation and restoration but is used mainly for smart grids and is proprietary.

III. Objectives of Proposed Application

There are many indicators of fault in a power gird, however, we focus on three major types of faults

1) **Blackouts:** This occurs when there is complete loss of electricity to a particular area in the power grid, it can be brief or prolonged.
2) **Brownouts:** This occurs when there is a temporary drop in the voltage of the electrical supply.
3) **Power Surges:** This is a spike of electricity which is usually very brief.

Of these three types of faults, blackouts can be the most costly and frustrating. It adversely affects customers as they no longer have access to electricity and the number of customers affected can range from a neighborhood to a town. It negatively affects the electrical company as they loose money and might have to replace or modify existing equipment. Hence, this fault will be the major focus of this paper. Brownouts occur during periods of heavy electricity consumption, while surges are caused by equipment along the transmission and distribution path.

Note that all of these conditions can be detected and monitored by the companies network of Intelligent Electronics Devices. However, if that system may fail because of inadequate maintenance of the network or simply lack of sufficient IEDs to detect all possible scenarios. The proposed application makes use of AMR readings and these tend to be robust because (a) such a network must be maintained since the companies revenues depend on the collected data and (b) a wide variety of readings are available since each customer has one of these meters. Therefore an application that depends on this information can be particularly robust.

IV. Application Details

The web application seeks to accurately and, in real-time, detect and isolate faults (see Section III) within a power gird. As stated previously, this application does not require any additional equipment or modifications to the network. It uses the readings from meters at customers' premises to be able to perform fault detection and isolation. Hence the system would need to be able to access these readings along with the GPS coordinates of each meter. Furthermore, it is assumed that each meter that is affected reports a Power Outage Notification (PON) and that when power is restored it also sends a Power Restore Notification (PRN). We also assume that the GPS

$S \leftarrow$ the set of meters
$L \leftarrow 1$ ▷ level counter
$F \leftarrow 0$ ▷ denotes the faulty component
while $F == 0$ **do** ▷ For each leaf k, A_k is ancestor list, if $k \in S$ reports PON then $x_k = 1$ else $x_k = 0$
    for all $k \in S$ **do**
        if $x_k == 1$ **then**
            if $F == 0$ **then**
                $F \leftarrow A_k(L)$
            else
                if $F \neq A_k(L)$ **then**
                    $L \leftarrow L + 1$
                    $F \leftarrow 0$
                    exit
                end if
            end if
        end if
    end for
end while

Fig. 2. Pseudo-code for determining faulty component

coordinates of other network components such as transformers and substations are also provided together with connecting transmission lines.

We model the transmission portion of the power grid as a mesh network and the distribution portion as a directed tree, rooted at the distribution substation with the leaves being the smart meters. Our focus is the failure of components in the distribution network (the distribution substation and transformers) and we ignore the transmission network which has significant redundancy due to its mesh layout. The children of the substations are transformers and the children of the transformers are smart meters.

We also model the wireless communication network that is used by meters to report energy usage and notification messages to a central server. This is a Frequency Hopping spread spectrum network and so the uplink is a shared medium. Therefore delays are not guaranteed but after a given report period, if a report is not received then we assume that the report will never be received. We therefore take into account the success probabilities of the reports in making decisions.

To determine the potentially faulty component we find the component that is most likely responsible given the list of meters that reported PONs (see [22] for details). Over time, as more PON reports are received, the probability that this component is responsible will increase or decrease. Once the probabilty exceeds some threshold we declare the component failed. Given the set of meters S, and assuming that a single fault occurred, the faulty component (node) is determined as follows. We find the closest common ancestor of all members of S that reported a PON. This can be computed using the pseudo-code provided in Figure 2 that has been taken from [22].

In addition to determining faults within the power grid, we also monitor the health of the network. On a periodic basis (e.g., every hour) we compute the average, over all meters, of the outage time over the prior period. This information is then plotted and so provides an indication of network health. Typically there should be some desired maximum for this metric and the utility company can use this to make maintenance and investment decisions.

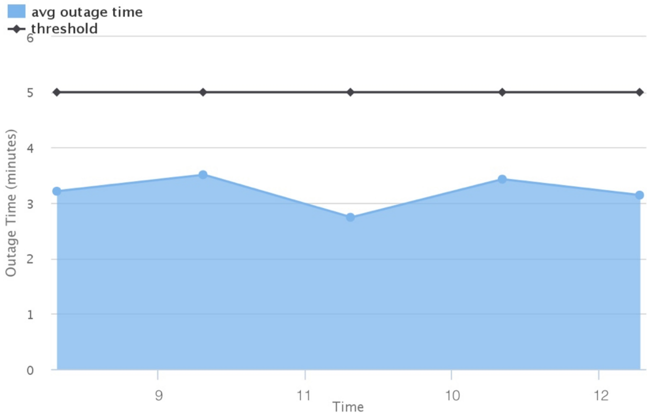


Fig. 3. Average user outage (per hour)

V. Application Features

In order to illustrate the application, we randomly generated user locations since (due to privacy issues) we could not use real customer locations. We then used a Markov model to generate PON and PRN notifications as well as other failures to illustrate the application.

A. Network Monitoring

Figure 3 shows the average outage time of all customers over the the past hour. The outages generated for this example were exaggerated to illustrate how the application works, since under normal conditions this metric will be zero. Note that a threshold is chosen and if this is exceeded alerts are generated (email, SMS etc) and sent to the appropriate managers. Naturally, the higher the metric value the higher up the management ladder the alert is sent. The graph also contains the actual number of customers that had no electricity in the past hour. Even if the outage metric is low, if the total number of customers is high then appropriate actions may be warranted.

Figure 4 shows the percentage of customers who have failures with their meters, be it an outage or other means. This is used to indicate possible problems with the communication network. If a large percentage of the meters are not reporting then appropriate managers are informed and the wireless network used for meter reporting is investigated. In this particular exaggerated example, we see that the highest percentage that is reach is approximately 11.8% which is under the threshold and so no alarm would sound. These graphs are complemented by real-time analysis of the power grid visually on a map.

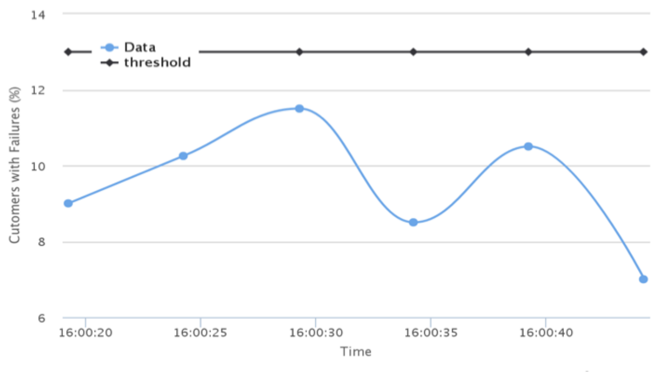


Fig. 4. Health of meter communication network

B. Power Grid Fault Detection

In this section we illustrate the fault detection features of the application. We again use randomly generated user locations and use a Markov Model for generating failures (i.e., a two state Markov Chain with states on and off).

Although the data used in our examples is generated, the data formats and other information conforms to those in a real system. For these illustrative examples we assume 400 meters connected to 20 transformers (each transformer supplies 20 houses with electricity), which are in turn are connected to 2 substations (each substation supplies 10 transformers with electricity), each getting its power from a single power generating station. We use the algorithm in Figure 2 to perform detection of faults in the power grid. Once started the map (Figure 5) is updated every 3 seconds and records any faulty components.

In Figure 5 the circular dots represent the meters of the customers. The larger square dots are the transformers and these are connected to 20 meters in its vicinity. The pins with the diamond shape are the two substations, each substation supplies electricity to half of the meters. Lastly, the pin in the center with the star inside of it is the power generating station and this provides electricity to the whole grid.

The nominal or fault-free grid would look like Figure 5a. All meters are green, all transformers, substations and the power station are blue (which indicates no fault). This is the ideal scenario, but unfortunately this is not always the case. Figure 5b shows what would happen if a transformer is fails. It shows that all the meters that are connected to the transformer turns yellow, corresponding to PON notifications received, and so the most likely faulty component is that particular transformer. The transformer's color is then changed from from blue to red to indicate this.

Another example is in Figure 5c, in which all the meters on the left of the map are yellow. In this case, it is unlikely that all the transformers in this area simultaneously failed, but more likely that the sub-station failed. Therefore, the sub-station color is changed to red. Finally, we illustrate what happens when a power generating station fails. Figure 5d shows that all meters have turned yellow and the most likely event of this failure is that of the power generating station and hence this icon's color is changed to red.

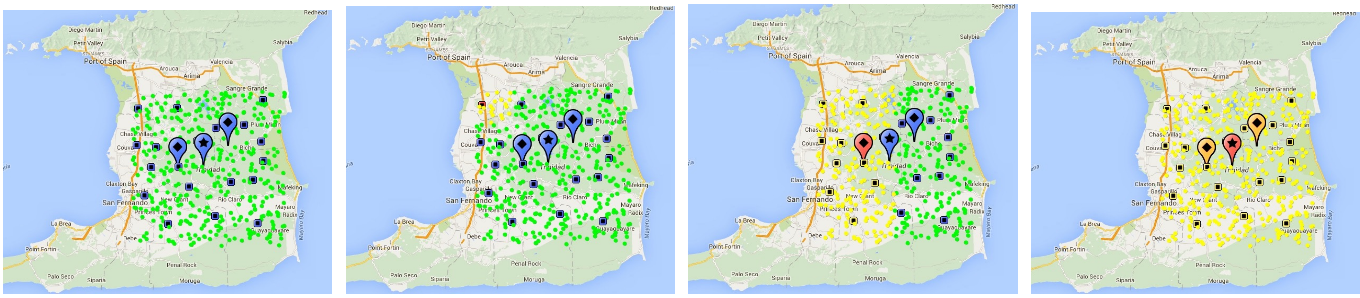
We want to emphasize that this simplistic version of the power grid may not be applicable to larger countries but is quite reasonable for smaller countries. Although the map is updated in near real-time, the time taken to detect a fault depends on the rate at which meters report PONs. This in turn depends on the architecture of the wireless network used for data collection. Because the uplink is a shared medium then as more meters report to a specific CCU the lower the reporting interval must be to accommodate them and hence the longer it takes to detect a fault. With typical parameters a fault can be detected within one or two minutes. Again, we emphasize that this application is used to complement other more sophisticated fault detection schemes that may be employed by the company.

When a fault is cleared, PRNs are reported and these are used to change the status of the various components on the map. The color of the meters that report PRNs are changed from yellow to green and the faulted component is also changed back to green. The application can therefore provide near real-time data to those who need information about the grid.

C. CCU Monitoring

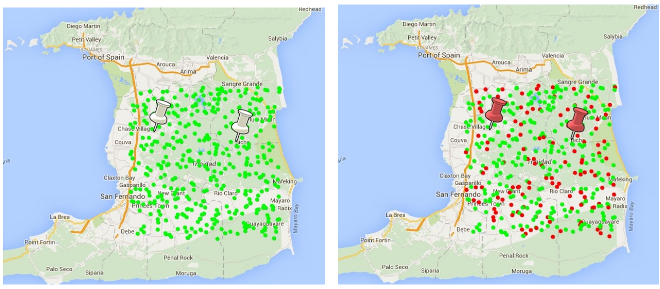
In addition to detecting and isolating the faults in the power grid, the application also monitors the health of the wireless network used for reporting meter data. Note, if a meter reports a PON then we do not expect energy usage readings from the meter until a PRN is received. However, if we do not receive a PON from a meter and we stop receiving energy usage information from the meter then something is wrong with either the meter or the wireless communication network. Figure 6 contains two maps with (a) showing the normal status of the wireless network under normal operations. When energy usage reports from a meter stops (e.g., no reading has been received within the last two reporting periods) then the meter icon is changed to red. These are monitored and if we notice several reds within a specific region, the network is investigated. In this particular case, the pins represent CCUs. If a CCU fails then many of the meters that normally provide reports through it will turn red and one can identify the failed CCU. However, multiple CCUs can receive reports from a single meter and so failure of a CCU will not result in all surrounding meters icons turning red. Note that once a energy usage report is received from a meter its icon color is switched back to green if it was red.

Due to space limitations we do not provide some additional functions that are included. The wireless network health is monitored in a similar fashion as for the power grid. On a periodic basis (e.g., every hour, the percentage of red meters compute the percentage of time that meters were in the red state (similar to the computation performed for outages). This percentage is plotted on a graph and a threshold is set. If this percentage exceeds the threshold then the appropriate staff are informed. In this particular case the required changes may



(a) Normal Operations (b) Failed Transformer (c) Failed Substation (d) Failed Power Station

Fig. 5. Fault detection in the power grid



(a) Normal Operations (b) Several Unresponsive Meters

Fig. 6. Detecting faults in the power grid

involve adding more CCUs or replacing faulty meters and hence can take significantly more time to resolve.

VI. Conclusions and Future Work

In this paper we provided a light-weight, open-source application which uses AMR meter readings (and nothing else) to detect faults in a power system for power grids in developing countries. The proposed scheme requires no additional equipment and can identify power grid faults in less time than it takes the crew to arrive. It works in real-time so that the utility company crew and management is always aware of the latest changes in the grid. It contains graphs that show the average outage time and the health of the power grid and maps that indicate the location of potential faults. It also detects faults and monitors the health of the wireless communication network.

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